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THE BEARINGS OF RADIOACTIVITY ON GEOLOGY

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To the geologist the center of interest in the phenomena of radioactivity lies in the spontaneous evolution of heat attending atomic disintegration. This interest is the more piquant because the source of the internal heat of the earth is one of the oldest of its problems and the discovery of radioactivity brings into the study an unexpected element. During the last century there was a rather general consensus of opinion that the earth's internal heat was derived from the condensation of the nebula from which the earth was then commonly supposed to have taken its origin. This nebula was usually regarded either as a gaseous body or as a quasi-gaseous meteoritic swarm, and in either case its condensation was thought to have given rise to intense heat. The primitive gaseous or quasi-gaseous earth-mass was held to have passed later into a molten globe, and the subsequent incrusting of this to have entrapped in the interior the heat supply of subsequent ages. This older view was still in general possession of the field when the apparition of radioactivity forced a new line of thought. But there was also an alternative view built on the belief that the earth grew up gradually by the slow accession of discrete orbital matter in distinction from the direct condensation of a gaseous or quasi-gaseous mass. In this view, the internal heat arose mainly from the self-compression of the earth-mass as it grew.

This view had its origin in the grave cosmogonic difficulties that had been discovered in the gaseous and quasi-gaseous theories of the earth's origin. Of the two rival views thus already in the field, the one postulated a plethora of heat at the outset and a gradual loss in all later time, the other postulated at the outset a more limited supply of heat which was increased as compression progressed. The adequacy of such compression to give a sufficiency of heat was a subject of debate from the inception of the view.[1] To the interest that naturally attaches to the discovery of a wholly unexpected agency, already acute because of the agent's singular qualities, there was thus added piquancy in view of its inevitable bearings on the thermal problem of the earth's interior and on the hypotheses of the earth's origin.

An even more fundamental though less imminent interest was awakened by the discovery that some of the atoms of the earth-substance are undergoing spontaneous disintegration and that all atoms may possibly be doing so and that even the permanency of terrestrial substance may be brought into question. However, matters of this ultra-radical nature cannot be discussed with advantage as yet, for little light has been shed on the broad question whether all terrestrial substance is in process of disintegration, and on the complementary question whether atoms are somewhere and somehow undergoing integration.

If the general tenor of the studies thus far made is to be trusted, nothing in the field of common experience seriously inhibits the dissolution of the radioactive substances. It does not appear that even the greatest heightening or lowering of temperature or pressure that can be brought to bear either stays or hastens, in any material measure, the progress of atomic disintegration. Nor do any known changes of chemical union or disunion, of concentration or diffusion, or of freedom or confinement seem materially to retard or accelerate the spontaneous dissolution. There is probably no warrant for an unqualified affirmation that neither temperature, pressure, concentration, exposure, nor combination

[1] The status of the problem of the earth's heat as it stood near the opening of the twentieth century is sketched more fully in *Year Book No. 2*, Carnegie Institution, 1903, 262–65, and in *Geology*, Chamberlin and Salisbury, I (1904), 533–47.

affects the progress of radioactive decomposition, but no specific effects of a critical value have been certainly disclosed by experimentation. These conditions that so much qualify most geologic processes must apparently be regarded as negligible for the present so far as radioactivity in the earth's crust is concerned. It is thought by the leaders in radioactive science permissible to treat radioactive substances as undergoing disintegration persistently and uniformly under all known terrestrial conditions. In the thermal problem of the earth radioactive particles may be dealt with tentatively as centers of heat-generation whose efficiency and endurance are conditioned simply by their atomic constitutions and their mass values. In so far as these remarkable deductions from experimentation may be thought to fall short of full warrant, weakness in equal degree must of course be held to enter into the geological inferences based on them; and in view of the radical nature of the conclusions to which they lead, we cannot perhaps too constantly bear in mind that the postulate of immunity to conditions is the main basis of the geologic contributions credited to radioactivity. But the remarkable verifications of skill and accuracy that have followed the multiplication of tests furnish an ample warrant for a serious discussion of present deductions. There is strong presumption that future tests will further substantiate present conclusions so far as their main bearings on immediate terrestrial problems are concerned, whatever interrogations one may be disposed to indulge in regarding ulterior problems.

The clue to this extraordinary tenacity of radioactive dissolution in spite of conditions that profoundly influence most terrestrial processes, probably lies in the fact that the action springs from the internal motions of the atomic constituents and that these are of such intense nature and are actuated by such prodigious energies that the influences of ordinary chemical and physical conditions are relatively insignificant.

At the same time, the radioactive substances show a decided aptitude to enter into chemical combination under common conditions. None of the parent radioactive metals is known to occur in the earth in a native state. In the form of compounds they have become widely distributed over the face of the globe in the

course of the surface changes it has undergone. Radioactive substances have freely entered into solution in the natural waters and have thus been carried wherever the hydrosphere reaches, and in turn they have been deposited therefrom. Their singular property of passing spontaneously from certain states into gaseous forms (emanations) and then back into the solid or liquid form, on definite time schedules, has caused them to be given forth freely into the atmosphere, and, drifting in this, to be later precipitated in the solid or liquid form, and this has naturally been dispersive in an extreme degree. Radioactive matter is therefore found in practically all the rocks of the surface of the earth, in practically all the waters, and in practically all the atmosphere.

But this highly diffusive distribution has not been uniform. There have been special tendencies toward concentration running hand in hand with the general tendencies to diffusion, and these concentrative tendencies constitute a critical element in this discussion.

So far as the accessible part of the earth is concerned, the igneous rocks may be taken as the original source of the radioactive substances. How the igneous rocks themselves came to have their present content will be considered later. Whence the radioactive substances came still more remotely is problematical. There may be even now accessions of radioactive substances from without the earth for aught that is known, and indeed this is probable; but, except in the form of meteorites whose content appears, from the few tests made, to be relatively meager,[1] such accessions are not yet demonstrated.

The cycle of distribution on the earth's surface is simple. From the igneous rocks the radioactive substances are dissolved and disseminated through the waters and carried wherever they go; while from both the rocks and the waters the emanations are given forth into the atmosphere. From the air and the waters in turn the radioactive derivatives are reconcentrated into the earth, except as their disintegration becomes complete and they pass permanently, in the form of helium, into the atmosphere or are lost from the atmosphere into the cosmic regions outside.

[1] Strutt, *Proc. Roy. Soc.*, LXXVII A, 480.

The special distribution of the radioactive substances among the different kinds of igneous rocks is no doubt full of meaning, but as yet the determinations have not been sufficient to justify more than a few broad generalizations, and these must be held subject to revision.[1] It may be said safely that the igneous rocks carry a higher ratio of radioactive substance than the average sediments. The reason for this is simple. The sediments are derived from the igneous rocks, and in the process of derivation some of the radioactive matter inevitably goes into the waters and into the atmosphere, and this diversion leaves the content in derivative rocks lower than that of the original rocks. If all the radioactive matter that is lost into the waters and the air were gathered into the derivative rocks, their content should equal that of the igneous rocks from which they came, if no account be taken of the loss by dissolution.

The earlier determinations of the amounts of radium in the igneous rocks by Strutt seemed to show that the acidic class hold more radioactive matter, on the average, than the basic class, and a portion of the later determinations seem to support this generalization, but the determinations of Eve and Joly, which have been important, seem to bring the richness of the basic class into somewhat near equality with that of the acidic, and even to make the preponderance of the one class over the other doubtful. The point of special interest here lies in the inference that, if the liquefaction and eruption of the igneous rocks is dependent on the heat derived from radioactivity, the distribution of radioactive substances in the erupted rocks should be inversely proportional to

[1] The larger number of determinations of radioactivity in rock have been made by Strutt: *Proc. Roy. Soc.*, LXXVI A (1905), 88 and 312; LXXXVII A (1906), 472; LXXVIII (1906–7), 150; LXXX A (1907–8), 572; Eve: *Phil. Mag.*, September, 1906, p. 189; February, 1907, p. 248; August, 1907, p. 231; October, 1908, p. 622; *Am. Jour. Sci.*, XXII, (December, 1906), 477; *Bull. Roy. Soc. Can.*, June, 1907, pp. 3 and 9; July, 1907, p. 196; Joly: *Nature*, January 24, 1907, p. 294; *Phil. Mag.*, March 1908, p. 385; *Radioactivity and Geology* (1909), general treatment with references; Elster and Geitel: *Phys. Zeit.*, II (1900–1901), 590; III (1901), 76.

For the physics of radioactivity see J. J. Thomson: *The Conduction of Electricity through Gases;* E. Rutherford: *Radioactivity;* (1904); *Radioactive Transformations* (1906); *F. Soddy: Radioactivity* (1904); *The Interpretation of Radium* (1909); R. J. Strutt: *The Becquerel Rays and the Properties of Radium* (1904); and the papers of Boltwood, McCoy, and many others.

their temperatures of mutual solution or of fusion. But it must be observed that even if such a casual distribution prevailed in the rock-matter when first it took the liquid form, this distribution might not persist indefinitely, for selective segregation has apparently taken place during the later processes. It is quite clear that the radioactivity is concentrated in some constituents rather than others, as for example in zircon, pyromorphite, apatite, and some other minerals, and in pegmatite and some other rocks. The pegmatitic material, in segregating from a granitic magma, seems to have gathered into itself an unusual proportion of the radioactive substance of the parent mass. In the details of final distribution, therefore, the different parts of the segregated rock-material may rationally be expected to differ from one another and from the parent magma in radioactive content. The determinations thus far made, though not adequate to demonstrate this, seem to be in consonance with it. Much interest will therefore gather about the forthcoming determinations as they multiply and contribute their quota of evidence bearing on the radioactive qualities of the various species of igneous rocks.

Among the derivative and sedimentary processes it seems clear that there are modes of concentration also which have given to different sediments different contents of radioactive substances. It appears from the determinations already made that the radioactive substances are leached out of the parent igneous rocks faster than the average minerals of those rocks, for weathered igneous rocks are found to carry less radioactive matter than fresh rocks. This is in accord with the aptitude for chemical change already noted; and yet soils which are almost the type of ultra-weathered material still retain notable radioactivity, but a part of this is probably a redeposit from the atmosphere. In general, it appears that the clayey element carries more radioactive material than the quartzose sands or the calcareous derivatives.

In the deep-sea deposits radioactive matter is higher than in the deposits of the shallow parts of the ocean. In the red clays and radiolarian oozes of the abysmal depths the content is markedly greater than in the land-girting muds and sands, or the calcareous oozes of mid-depths. This is assigned in part to the removal by

solution of the lime from the original matter of the abysmal deposits, leaving them residual concentrates, and in part to the collection in the depths, in relatively high proportions, of phosphate-bearing relics (teeth, bones, etc.) with which radioactive substances are associated. It is a suggestive fact that the phosphatic nodules of the great deeps are highly radioactive compared with ordinary sedimentary material. A part of this is clearly due to the concentration of the radioactive substances after the phosphates were deposited, for fresh phosphatic material is notably less radioactive than fossilized phosphates.[1]

It appears then that the radioactive substances on the surface of the earth are subject to special agencies that lead in part to greater concentration and in part to wider distribution, and that these act co-ordinately with the general dispersing agencies that give radioactivity to the derivative rocks, to the waters, and to the air.

If it were permissible to reason from what is known of surface phenomena, particularly from the broad fact that radioactivity increases as we go from air to water, from water to sediment, and from sediment to igneous rock, it might be inferred very plausibly that radioactivity would be found to reach its maximum concentration in the heart of the earth, and certainly that the deeper parts would be as rich as the superficial ones. This presumption might very justly be felt to be strengthened by the fact that the atoms of uranium, radium, and thorium are among the heaviest known and that if the earth were ever gaseous or liquid, these heavy atoms might naturally be expected to be concentrated toward its center unless the viscosity of the fluid mass were too great to permit this, in which case the distribution should be either equable or indifferent to depth.

But Strutt[2] early called attention to the fact that if such an increasing abundance exists toward the center of the earth, or if there were an equable distribution in depth, the heat gradient as the earth is penetrated would be higher than observation shows it to be. By computations on the data then available he

[1] Strutt, *Proc. Roy. Soc.*, LXXX A, 582.

[2] *Proc. Roy. Soc.*, LXXVII A (1906), 472; LXXVIII A, 150.

concluded that a distribution of radioactive substance equal to that of the surface rocks for a depth of only 45 miles would give the rise of heat actually observed in wells, mines and other deep excavations. Later data and closer scrutiny seem to confirm the general soundness of Strutt's inference, and to make the limitations even more narrow. Joly, approaching the problem from the geological as well as the physical point of view, and with the advantage of later data, reached the conclusion that radioactivity of the amount observed at the surface, if continued to a depth ranging from 27 to 37 kilometers (17.2 to 23.5 miles), would give rise to heat equal to that implied by the loss at the surface.[1] According to Joly, however, a complete concentration of radioactivity in a shell of this depth does not meet the apparent requirements of igneous phenomena if this be assigned to radioactivity. A deeper distribution of a part of the radioactive matter and a less concentration in the outer part of the crust is felt by Joly to be required and he was led to this final statement: "If we said that the richer part of the crust must be between 9 and 15 kilometers deep, we cannot be far from the truth. This appears to be the best we can do on our present knowledge."[2] It is to be noted that these deductions are reached on the supposition that all the internal heat given out arises from radioactivity; no margin is left for any original heat or for secular heat from any other source. On the other hand, the computations seem to take no account of loss of heat by means of igneous extrusions.

These remarkable deductions raise two questions of radical import:

(1) If supplies of heat are generated currently by radioactivity in such abundance that it is necessary to put these severe limits on the distribution of radioactive substances, must we abandon entirely all further consideration of supposed supplies handed down from a white-hot earth or from any other form of the primitive earth?

(2) Is there among the internal processes previously postulated any that provides a way in which such a concentration at

[1] *Radioactivity and Geology* (1909), 175.

[2] *Ibid.*, 183.

the surface might naturally have taken place, or must we find a new geological process to fit the new thermal difficulty?

The rigor of the dilemma is softened somewhat by noting that the deductions of Strutt, Joly, and their colleagues are based simply on comparisons between the heat-generating power of radioactive substances in the crust and the conductive power of the crust. The functions of igneous extrusion as a mode of transfer of internal heat do not seem to be taken into account. This is not unnatural since the heat carried out by extrusive matter and by waters heated by igneous intrusions has not usually been regarded as an important factor in reducing the high temperature inherited by the earth under the older view. But the movement of igneous matter and of waters and gases heated by it has been made to play an essential part in the working concepts that have been based on the planetesimal hypothesis. There will be occasion to return to this critical difference of view.

When the apparent excess of thermal riches arising from the new source was first realized an escape from the dilemma raised by it was sought in the natural supposition that the disintegration of uranium and thorium was restrained by pressure in the depths of the earth, and that, though present there, their activity was greatly subdued or possibly inhibited altogether. This plausible explanation was diligently tested; but the general tenor of experiments on the effects of pressure, notably those of Eve and Adams[1] in which the pressures were carried to intensities sufficient to cover earth-pressures to the depths supposed to limit radioactivity and beyond, showed no appreciable restraint on the disintegrating process. It seems necessary, therefore, in the present state of evidence, to accept the inference that the radioactive substances are really concentrated toward the surface, and that the radioactive content in the depths of the earth is of a much lower order.

It does not fall to me to adjust the new requirements to the older view of the earth's internal temperatures based on a molten earth, for other considerations led me to the abandonment of this view before the advent of the new issue. I must leave it to those who hold to the molten hypothesis to battle with its new perils.

[1] *Nature*, July, 1907, p. 269.

With such a plethora of heat at the start as a molten earth implies and with a new agency whose current production of heat would seem to be excessively great if its prevalence were not constructively minimized, it is not with regret that I feel absolved from the task of finding a reconciliation between this venerable view and the requirements of juvenile discoveries.

The discussion of Professor Joly,[1] though not explicitly based on the theory of a molten earth, is sympathetic with the general tenets associated with such an earth, and his treatment may be taken as offering the best approach to a reconciliation that seems now possible.

It is interesting to note, however, that when Professor Joly reached the critical question of a possible mode by which the surface concentration of radioactivity could have come about (*Radioactivity and Geology*, 184) he turned to the accretion or planetesimal hypothesis. While he indicated the central line of action on which the concentration might have been accomplished he left without elucidation the line of reconciliation between the heat gradient postulated by the planetesimal view and the gradient he deduces from radioactivity.

It is the chief purpose of this paper to set forth what seems to me to be the true harmony between the new light shed by radioactivity and the tenets of the planetesimal view as shaped by me before the discovery of radioactivity and to show the co-ordination of the planetesimal and radioactive agencies in jointly leading to the results observed. To this end it is necessary to sketch with some care the thermal features of the planetesimal view in the form to which preference was given from the start so that it may be clear just what part radioactivity plays in the assigned co-operation.

On the assumption that the earth grew up by the accession of planetesimals, whatsoever heat arose from the condensation of the nucleus about which the growth took place centered in the innermost parts and can affect present surface phenomena only by transfer. The infalling matter that is supposed to have built up the earth to its mature size must have generated much heat by

[1] *Radioactivity and Geology*, 154–82.

its impacts, but as the infall is held to have been slow and as this heat was superficial, it may be assumed that it was largely radiated away before it became so deeply buried as to be permanently retained, and so the most of the heat of impact may be regarded as negligible.[1] In the original shaping of the planetesimal hypothesis (before the discovery of radioactivity) the main source of internal heat was made to spring from the compression which the deeper parts of the earth underwent by the increase of its mass as the planet grew to maturity. This chief source was supposed to be abetted by heat springing from the rearrangment and recombination of molecules within the mass as time went on. Changes in the distribution of the heat after it was developed were supposed to follow by means of conduction and especially by the transfer of hot fluid matter carrying latent heat.

It is important to the present discussion to note that the heat generated by pressure did not affect the outer part and that it began to be sensible only when those depths were reached at which the rocks suffered appreciable compression from the weight of the rock-mass above them. Thus the heat gradient so generated would rise only slowly in the outer part of the earth and faster in a systematic way toward the center for a considerable depth, if the compressibility of the rocks remained uniform to indefinite depths. If the compressibility fell off as compactness increased the rate of thermal rise toward the center would have been slower. Compressibility at the surface seems to be nearly proportional to pressure, but the compressibility of rocks after they have been compacted by such pressures as are attained at considerable depths is unknown, and it is necessary to proceed here by alternative hypotheses. The extrapolation of the curve found under experimental pressures is of course entitled to precedence and this alternative was used as the basis of the first approximation to the heat curve of the earth's interior. For the other factors, such as specific heat, necessarily taken into account in the computation, assumptions as near to known facts as possible were made. On these assumptions it was found that the heat generated between the surface and the center of the earth may be represented by a curve

[1] Chamberlin and Salisbury, *Geology*, I, 533.

which rises at a very low rate near the surface and is followed by a slowly *increasing* rate for about one-third the distance to the center, beyond which it rises at a *decreasing* rate to the center; or, if traced from the center outward, this computed curve of temperature declines faster and faster at every step for about two-thirds of the distance and then declines less and less rapidly to a vanishing-point near the surface. Hence if conductivity be assumed to be the same at all depths, the outward flow of heat on such a gradient would increase in rate from the center to the two-thirds point and then grow slower toward the surface, from which it follows that, on these assumptions of uniform compressibility and uniform conductivity taken by themselves, the internal heat should have been progressively lowered in the deep interior and raised in the more superficial parts. The conductivity of rocks is so very slow, however, that its effects at the surface under the conditions named cannot have been large up to the present unless the earth is much older than even radioactivity seems to imply.

This first approximation to a theoretical curve of heat, even when modified by conduction, has not been supposed to represent the actual distribution of heat at the present time, for reasons that follow.

There is ground to think that compressibility falls off as increased degrees of compactness are attained. In working out the curve which was published in *Geology*, I, 566 (Chamberlin and Salisbury), Dr. Lunn used as a guide the Laplacian law of density which postulates that density varies as the square root of the pressure. This distribution of density harmonizes fairly well with such astronomical tests as are available and gives a mean density for the earth which is near that required by the earth's total weight. The assumption that the increased density of the interior is all due to compression, however, makes no allowance for the probable transfer of lighter matter to or toward the surface by extrusive action which would tend to increase the mean specific gravity of the residue. The curve of Dr. Lunn may be regarded as a second approximation.[1] But this, as noted, does

[1] *Year Book No. 3*, Carnegie Institution of Washington, 1904, p. 156; also "Geophysical Theory under the Planetesimal Hypothesis," Section II of "Tidal and Other

not take into consideratiion the effects of liquefaction and extrusion and these in the planetesimal view are of the first order of importance. The theoretical curve mathematically deduced by Dr. Lunn is, however, an indispensable basis for a third approximation in which the effects of liquefaction and extrusion are taken into account.

Before passing on to consider liquefaction and extrusion, it is well to note that the Lunn curve based on the Laplacian law of density also is low near the surface and that its rate of rise is much below that of the temperature gradient observed in wells and mines. Dr. Lunn, on assumptions carefully specified in his discussion in the paper cited, found the rise in the first 200 miles only 330° C.

This low development of heat in the outer part of the earth seemed at first thought to present a difficulty of a rather serious nature, but it was believed to be met by the effects of liquefaction and extrusion, and these were made the chief basis of an additional approximation to the actual temperature curve (Chamberlin and Salisbury, *Geology*, I, 265–67). It was held that the rising heat of the interior would reach the temperatures of fusion or of mutual solution of some ingredients in the mixed material much earlier than that of other ingredients, and that the ascent of the portion that became molten carrying its latent as well as sensible heat into the cooler outer zone would necessarily raise the temperature of that zone. It was held that the continuation of this process served as a constant influence tending to retard the rise of temperature in the deeper zone where the partial liquefaction was in progress while it progressively raised that of the outer zone into which the liquid rock was intruded, whether it lodged in the crust or passed through it to the surface. This extrusive process was supposed to have continued to the present day and to have resulted in a permanent adjustable working curve of accommodation between thermal, fluidal, and mechanical conditions. This curve, except in the cool crust, was essentially identical with the fusion-

Problems," *Publication No. 107*, Carnegie Institution of Washington, 1909, pp. 169–231; for a summary and figure of curve see also Chamberlin and Salisbury, *Geology* (1904), I, 566.

solution curve, whatever that might happen to have been for the time being under the local conditions of pressure, state of strain, nature of material, means of escape, and other properties that affected liquefaction and extrusion. It was regarded as essentially *a curve of equilibrium between solidity and liquefaction* accommodated to the conditions present at each depth and at each stage and was *maintained automatically. The actual curve as thus assigned continued always to be essentially the liquefaction curve after that was once attained.*[1] The view excludes automatically all internal temperatures higher than the local liquefaction temperatures and of course excludes all pervasive gaseous conditions except that of the interspersed and occluded gases of the mixed mass. These interspersed gases assisted extrusion and hence were among the parts most freely extruded. All theoretical inferences based on temperatures higher than the temperatures of liquefaction are excluded from consideration under this view by its very terms.

Certain structural conditions postulated by the planetesimal hypothesis greatly favored this automatic action. The infalling matter was assumed to have built itself up in a very heterogeneous manner with the result that the mass of the earth was an intimate mixture of all the kinds of material that made up the spiral nebula from which it was supposed to have been gathered. As this mixed matter was heated by compression, some parts of it must certainly have reached temperatures at which they could go into mutual solution or into fusion while as yet other closely associated parts had not reached temperatures that permitted such action, and as the rise of temperature was very slow by the terms of the hypothesis the passage of successive parts into liquefaction was widely separated in time. Fluid parts thus came temporarily to be intimately mixed with solid parts. These fluid parts, in the act of passing into solution or fusion, absorbed the necessary energy of liquefaction at the expense of the increasing supply. On their ascent into the crust they heated it. If they lodged there and resolidified they gave up their heat of liquefaction. If they reached the surface the residue of heat, both sensible and latent, was lost. By such liquefaction and transfer these portions served

[1] *Op. cit.*, 567.

to protect the residue in the deeper parts from liquefaction for the time being and the continuation of the process extended the protection to such residue as continued to persist.

It is not necessary to offer evidence that ascent of liquid rock took place in great quantities in the early geologic ages and has been more or less active in all ages down to the present. One of the extraordinary facts of the Archaean terranes is the extensive lodgment of liquid rock in the crust, and even in later ages batholitic phenomena have attained surprising magnitudes. The extrusion of molten rock at the surface was a very pronounced phenomenon as late as the Tertiary and is still an active process. As this extrusive action was widely distributed over the surface at various altitudes and at various stages through great lapses of time and yet was never really very massive when measured in terms of earth-volumes at any one time or place, it is of critical value here to note that the view built on the planetesimal hypothesis appeals to a special set of conditions of liquefaction and extrusion which are peculiarly favorable for selective work in small masses and unfavorable for *general* liquefaction. In this respect the conditions it assigns stand somewhat in contrast with the conditions usually assumed to be the natural inheritances from a general molten condition. The inference that *general* liquefaction would take place on any general rise of heat is natural enough in a case in which the whole mass has been solidified from a previous molten state, for such a mass might be presumed to return massively into its former state on a reversal of conditions; but the heterogeneous condition of the mixed matter of the interior postulated by the planetesimal view is not favorable to a simultaneous fusion of the whole mass or any large continuous part of it unless extrusion be restrained until a high temperature is attained. Such restraint is here held to be dynamically inconsistent with the mechanism and the stress conditions of the earth-body. In addition, therefore, to such a mixed state of material in the interior as peculiarly to invite selective liquefaction as the temperature slowly rose, the planetesimal view postulates a set of stress agencies that worked co-operatively to effect extrusion as fast as liquid matter accumulated in workable volume.

In considering stress effects, it is necessary scrupulously to distinguish between *hydrostatic* stresses which operate equally on all sides of a given unit and so only produce compressive and like effects, and *differential* stresses which promote movement and change of form. The effect of differential stresses on the solid parts of the earth is primarily to produce strains; the effect on liquid parts is primarily to produce flow and relocalization. And so by reason of this difference of effect, a general differential stress on any large part of the earth is apt to become locally sub-differentiated when solid and liquid parts are intermixed, especially if the liquid and solid states of these parts are partially interchangeable because their temperatures lie so close to the line of equilibrium between solidity and liquidity. Tensional strains promote liquefaction in bodies constituted as most rocks are; compressive strains resist liquefaction in such bodies. And so general differential strains co-operate with temperature in promoting or in restraining the passage of matter from the one state to the other according to the nature of the strain and thus have some influence in directing and facilitating movement as well as in forcing it.

Some of the differential stresses in the earth are essentially fixed and constant, such as the direct pressures that arise from the action of gravity. These stresses range from one atmosphere at the surface to about three million atmospheres at the center. Such pressures tend to force lighter bodies toward the surface while heavier bodies seek the center in ways so familiar that we need not dwell on them, nor on the fact that, since molten rock is usually lighter than the same rock in a solid state, this static differential stress of gravity presents a general condition that favors the ascent of liquid rock. So also the incorporation or generation of gases in liquid rocks tends to lessen the specific gravity and increase the mobility and hence the gaseous element adds another general influence that favors ascent.

In addition to these very general and persistent stresses, more special differential stresses have arisen at various times from inequalities of accession, from transfers of matter, from loss of heat, and from other varying agencies, and these have been present,

in one form or another, at nearly all times in the earth's history. They have often been cumulative until they reached diastrophic intensity and manifested themselves in impressive deformations. That these have been effective agencies in forcing the movement of liquid parts within the earth in the lines of least resistance and of best accommodation to existent conditions is scarcely debatable.

In addition to the simple stresses of gravity and to the diastrophic stresses, there have been superposed at all times a series of stresses of a rhythmical pulsatory nature acting throughout the body of the earth. The nature and function of these has not been so generally recognized. These stresses are derived from the differential action of the gravity of neighboring bodies, particularly that of the moon and of the sun. Tidal and tidelike stresses and strains have swept through the earth's body in a constant cycle bringing to bear on each part a perpetual succession of compressive and tensional stresses and strains alternating with one another. The effect may be pictured as that of a minute kneading of the earth-body. There is not only a superposition of pulsating strains on the more static strains but a superposition of pulsating strains on pulsating strains. The pulses of the twelve-hour body tides are overrun by tides of longer periods and these are attended by shifts of direction of strain, all of which tend to knead the mixed matter to and fro and promote insinuation of the liquid parts along the lines of escape.

Underlying all these rhythmical strains there has been ever present a variation in intensity from center to surface. Sir George Darwin has shown that the tidal stresses generated by the moon at the earth's center are eight times as great as those at its surface. Each compressive strain squeezes the lower part of each liquid vesicle or thread more than the upper part.

The coexistence of these pulsatory and periodic strains with the simple static stresses of gravity and the less constant diastrophic stresses sufficiently implies their co-operative nature. All these three classes are either differential stresses or have factors or phases that are differential, and so, in specific local application, they are all transformed into sub-differentiational effects on the liquid and solid parts.

Under the planetesimal view the joint effect of these differential stresses and their resulting strains has been at all times to force toward the surface liquefied rock as fast as it gained workable volume. Much aid in insinuating itself along liquid lines and in fluxing a more open path until the fracture zone was reached, is assigned to the mixed nature of the material and to the local strains imposed by the stress agencies. The whole picture centers on the fundamental dynamic proposition that *energy in mobile and expansive embodiments seeks the surface, while its fixed embodiments are forced more firmly together toward the center.*

The extrusion is held to have begun as soon as the susceptible matter took the mobile form. Possible exception is admitted in the case of matter that may have been too dense to be forced to the surface. However, a high density of small masses enmeshed in masses of less density could only contribute to an average effect so long as a high state of viscosity was retained, and a relatively high viscosity for the small mobile masses, naturally arose from the close balance between the liquid and solid states. Such a condition seems equally to be implied by the remarkable mixtures of dense and light matter often seen in the igneous rocks.[1]

The matter forced early to the surface is held to have been buried by further accretions to the growing planet, later to have been subject to a second liquefaction and extrusion, a second burial, and so on. Progressive selection and reselection are postulated until the growth essentially ceased. Since then a more complete selection and concentration of the eutectic material at the surface has been in progress as far as further generation of internal heat has furnished the actuating agency.

Now if this picture in its working details and in its rather sharp antithesis to the older view is clearly in mind, the part which the radioactive substances may be supposed to play in co-operation with this mechanism without changing the general conception is little less than self-evident. The radioactive particles are sources of self-generated heat. Under the planetesimal view the radioactive substances were promiscuously scattered through the mixed mass as it was gathered in heterogeneously from the nebula

[1] Chamberlin and Salisbury, *Geology*, II, 121–22.

by the crossing of the planetesimal orbits. No original segregation of this class of matter more than of any other heavy material is assignable. The relative amount of the radioactive matter, at least of the classes now known to be radioactive, must have been extremely small and its influence on the specific gravity of the matter with which it was mixed must have been negligible. The self-heating effects of these disseminated particles were necessarily expended first upon themselves and next upon adjacent matter, and, other things being equal, this homemade heat should have given these parts precedence in passing into the mobile state. Normally the mixed units that inclosed a radioactive particle should have been as susceptible of partially passing into the liquid state as similar units that were free from radioactive matter. The special source of heat should have turned the balance in favor of the unit immediately surrounding the radioactive particle. Thus the radioactive matter normally became involved in the mobile matter and passed with it to or toward the surface.

With every stage in the growth of the earth and with every reburial of the radioactive material a second similar preferential action should have followed. On the essential completion of the growth of the earth a more complete concentration of the self-heating matter should have followed, for additional weighting by accretion had essentially ceased and compression had become essentially static while the self-heating competency of the radioactive matter, though no doubt somewhat reduced by consumption, was probably more efficient *relatively* in the production of heat than it had been during the more active stages of growth.

It seems clear, therefore, that at all times after the volcanic process was well under way radioactivity should have been relatively most active in the outer part of the earth and should have become especially so in the latest stages of the earth. It is therefore not too much, perhaps, to claim that a specific basis in favorable conditions and a definite working mechanism for an effective concentration of self-liquefying matter at the surface was postulated in a singularly apt way before radioactivity was discovered, and quite irrespective of the dilemma which its discovery has involved.

Reciprocally radioactivity greatly eases the burden laid on compression in the outer part of the earth where it is least competent and where resort was had to igneous intrusions from below to give the crust its observed temperatures. With the addition of the new thermal agency the extrusions are presumed to play much the same part as before but more actively, as they must now be supposed to meet the liquefying effects both of compression and of radioactivity. If there was ground before to question the efficiency of compressional heat, aided by such other sources as were formerly assignable, to give rise to the high degree of igneous activity that marked the Archaean ages and to sustain the lesser igneous action of later periods down to the present, this doubt is amply resolved by the combined efficiency of compression and radioactivity. In any case it is certain that a large amount of energy has been brought to the surface and radiated into space.

Radioactivity also comes to the aid of other agencies of extrusion in the peculiar service it renders in opening a path for the outward movement of the liquid matter. In the liquefying process, as we have seen, the radioactive particles should have been gathered by their self-heating action into the liquid vesicles and have been forced outward with them. The self-heating property thus became an endowment of the liquid and gave to it thermal efficiency in dissolving and fluxing its way. This efficiency was continually renewed by the progressive disintegration of the radioactive atoms. It is not improbable that the liquid threads were thus aided in a very special way in boring upward, for it seems obvious that the part of the liquid which carried most of the self-heating constituent would come to have the highest temperature, the lowest specific gravity, and the largest gaseous factor—for the disintegration produced gas emanation and helium in addition to the gases generated by the heat alone—and hence would take the uppermost position and bring its liquefying influences to bear on the solid matter which lay between it and the surface toward which it was pressed. The very mechanism may thus have kept the most effective part at the point most critical to its ascent.

While this outline falls far short of an adequate discussion of the relations of radioactivity to the planetesimal hypothesis, it

will perhaps suffice to point out the line of co-operation of the new thermal agency with the new genetic hypothesis. The two seem to co-operate happily. Jointly they seem to furnish a promising basis for a revised thermal geology in harmony with accumulating geologic data in various lines and with the growing evidence of the elastic rigidity of the earth-body as a whole. At least the concentration of the radioactive substances at the surface seems to be aptly explained, and the mechanism that conserves the solidity of the earth falls into consonance with the new experimental evidence of an elastico-rigid body-tide which seems scarcely less than decisive.

There is perhaps one further point, among the many remaining, that should be briefly touched here lest there seem to be an outstanding incongruity in the present distribution of vulcanism. If there is a progressive supply of heat in the earth's crust springing from radioactivity and if it is this that actuates vulcanism, why are not volcanoes more uniformly distributed over the face of the globe? A general sub-uniform distribution is a natural deduction from the postulates. The distribution of pits on the moon, assuming that they are volcanic craters, fairly fits the picture that normally arises from the action of such an agency. Especially is this true if vulcanism is effected in so selective and so individual a way as we have indicated. Why has not such a distribution persisted on the earth? It will perhaps be conceded that the prevalence of vulcanism in Archaean times fairly satisfies the terms of the case. But at present volcanoes are rare in the primitive shields that form the nuclei of the continents while volcanoes are concentrated about the borders of the continents and in the deep basins and are particularly abundant where the great segments of the crust join one another. The primitive shields are indeed intimately scarred and shotted with igneous intrusions of the early ages, but they are almost immune now.

There seem to be two lines of plausible explanation. These old embossments have suffered denudation from an early date and the matter removed has been carried to the borders of the adjacent basins. According to the hypothesis of concentration at the surface, this lost matter carried a relatively high proportion

of radioactive substance. When this was in the state of a mechanical sediment it was chiefly deposited on the borders of the basins; when it was in solution it mixed with the waters of the oceans and was later largely concentrated in the oceanic precipitates. Thus the prolonged process of denudation cut away the radioactively richer part of the shield and added it to the undenuded crust of the continental borders and the oceanic basins, thinning the one and thickening the other in a special radioactive sense. Besides this the lower crust in the denuded area was lifted relatively toward the cold surface, while in the depositional area it was relatively depressed beneath a growing radioactive mantle.

The rise of the denuded embossments of the crust was attended by elastic expansion of the whole sector of the earth beneath, since the gravitative pressure was lessened throughout. A lowering of the melting-points indeed attended this and doubtless a change also of the mutual-solution conditions, but this was anticipated by the elastic expansion and its instantaneous cooling effects, a point usually overlooked.

In addition to this immediate expansional effect, it is held by some geologists, with whom I am glad to associate myself, that the protruding portions of the continents tend to lateral creep and that this carries with it tensional effects as well as some further elastic expansion. At the same time, the penetration of surface-water is promoted and this aids effectively in carrying off the heat of the outer crust. It may be observed that while meteoric circulation penetrates to considerable depths beneath land surfaces there is little reason to think that there is any effective circulation to appreciable depths in the ocean beds.

One further agency is believed to co-operate with these at a lower horizon but this can be touched only with reserve as it involves joint studies yet in progress upon which I do not feel at liberty to draw further than may be necessary merely to indicate their bearing on this particular problem.[1] In a previous part of

[1] The studies are common to my son, Rollin T. Chamberlin, and myself and in the particular here applicable the junior partner is the leader in pursuance of lines of inquiry growing out of his studies on "The Appalachian Folds of Central Pennsylvania," *Journal of Geology*, XVIII, No. 3 (April-May, 1910).

this paper the selective influence of strains on fusion and solution was cited. There seems little doubt that a similar influence is exerted by the great zones of strain that are developed in the earth by diastrophic agencies. Among the tentative distributions of these under study, a specific system seems more probable than others and this is of such a nature as to direct fluid matter, particularly any that may arise at considerable depths, toward the lines that are affected by volcanic extrusions.

THE WING-FINGER OF PTERODACTYLS, WITH RESTORATION OF NYCTOSAURUS

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The question whether the wing-finger of pterodactyls is the fourth or the fifth has been disputed for the past eighty years, though for the past forty years authors have been almost unanimously agreed that it is the fifth. The first writer of credibility who expressed an opinion on the subject was Cuvier, who considered it the fourth. His reasons for so doing, as published in his Ossemens Fossiles, are today, I believe, unanswerable, and to him should be given the credit, and not to H. v. Meyer, for the correct recognition of the finger. I quote his remarks in full:

> En fin il a ce doigt énormément prolongé en tige grêle, qui caractérise éminement notre animal.
>
> Il a quatre articulations sans ongle. Le quatrième doigt des lézards aurait cinq articles et un ongle; mais, dans les crocodiles, il n'a que quatre articles, et il est dépourvu d'ongle comme ici; seulement il n'y éprouve pas ce prolongement extraordinaire.
>
> Le crocodile et les lézards ont en outre un cinquième doigt qui dans les lézards a quatre articles, et dans le crocodile est réduit à trois sans ongle.
>
> Il paraît que dans l'animal fossile il ne reste qu'un vestige de cinquième doigt, mais assez obscur et sujet à contestation.
>
> Le grand doigt est probablement le quatrième, car c'est aussi le quatrième qui est le plus long dans les lézards.
>
> Les trois autres le précédaient dans l'ordre inverse du nombre de leurs articles.

The first author to adopt the other view, that the finger is in reality the fifth, was Goldfuss, who, as Plieninger has shown in his full and reliable review of the subject, thought he saw in the pteroid bone a first finger, accidentally misplaced in his specimen, and in which he thought he recognized an additional phalange even. H. v. Meyer early adopted Goldfuss' view, as shown in the following quotation: "Es zeichnen sich diese Thiere vor allen anderen wirklich dadurch aus, dass der Finger sie zum Fliegen befähigte,

und zwar nur ein Finger, die Ohrfinger, welche wegen der Kleinheit womit er in der Hand anderen Geschöpfe sich darstellt auch der kleine Finger genannt wird" (*Paleontographica* [1851], 19).

But Meyer soon returned to the Cuvierian position, calling the first of the small, clawed fingers the thumb. I can find no independent arguments of Meyer giving the reasons for his views; indeed in various places he is more or less obscure, referring to the "Flugfinger" as the "Ohrfinger," though there can be no doubt but that as early as 1860 he had, as I think, correctly recognized the digit as the fourth. Owen in his *Paleontology* and *Comparative Anatomy of Vertebrates* figures four small, clawed fingers in front of the wing-finger, which he calls the fifth. Later he reverted to the Cuvierian view. Goldfuss's views were followed by Oscar Fraas and most modern authors, including Marsh, Zittel, Plieninger, and Eaton. In 1904,[1] without at the time having read Cuvier's remarks on the subject, I published a brief article in the London *Geological Magazine* giving reasons for the older view, that the finger is in reality the fourth, as based chiefly upon the recognized normal number of phalanges in the hands of reptiles.

FIG. 1.—Restoration of *Nyctosaurus gracilis* Marsh, by Herrick E. Wilson

[1] "The Fingers of Pterodactyls," *The Geological Magazine*, 1904, p. 59.

Two years later Plieninger[1] discussed the subject fully and well, reaching no positive conclusion, though evidently favoring the Goldfuss view that the finger is the fifth. He showed that Goldfuss, and not Fraas, as I had thought, was the first author to suggest the identification of the pteroid with the first finger, and corrected Seeley's statement that Meyer had so recognized it. We have seen from the quotation that Seeley was really not so far wrong after all, since Meyer did at one time consider the "Flugfinger" as the "Ohrfinger." Finally Abel[2] in a recent paper has restated the problem, adopting the original Cuvierian view.

As bearing upon this question we have been fortunate in recent years in determining the intimate structure of the hands and feet of several of the early reptiles, from which I may say with entire assurance that, until the close of Carboniferous times, and probably till the close of Permian times, the phalangeal formula for reptiles was the primitive one of 2, 3, 4, 5, 3 for the front feet; 2, 3, 4, 5, 4 for the hind. Plieninger has raised a question in the cited paper whether the formula 2, 3, 4, 4, 3, as seen in the crocodiles, was not really the primitive one for the hands instead of 2, 3, 4, 5, 3, as found in the generality of modern lizards and in *Sphenodon*. In the accompanying figures the front limbs of three of these reptiles, from the so-called Permian of Texas and New Mexico, are shown, made out with certainty in nearly every detail. In Fig. 4 the distal three phalanges of the fourth finger have not yet been positively fixed, but inasmuch as the fourth digit of the hind foot of the skeleton to which the figured hand pertains has definitely five phalanges, there can be no doubt of the number in the same digit of the hand. In Figs. 2 and 4 the bones of the forearm and wrist are shown in a horizontal plane without the foreshortening of the oblique position that they really had in life, and which is shown in Fig. 3. Fig. 2 is that of a cotylosaur, probably belonging in the suborder Pareiasauria, while Figs. 3 and 4, *Ophiacodon*[3] and *Vara-*

[1] "Ueber die Hand der Pterosaurier," *Centralbl. für Mineralogie, Geol., etc.*, 1906, p 399; also *Paleontographica*, LIII (1907), 301.

[2] "Die Vorfahren der Vögel," *Verhandl. der K.K. zoologisch-bot. Gesellsch.*, LXI (1911), 163.

[3] The full description of this genus will appear shortly in a paper by Dr. Case and the writer.

nosaurus, are zygocrotaphic reptiles that may be included in the order Theromorpha or Pelycosauria.

FIG. 2.—Right front leg of *Limnoscelis* Williston, a cotylosaur reptile from the Permian of New Mexico. A little less than one-half natural size.

In all these forms it will be observed that the fifth digit is much reduced, more so than in the hind feet of the same animals. The number of phalanges in this finger in each is three and no more; this is positive. Furthermore it will also be observed that the supporting carpale 5 is reduced or wanting in all; that is, the loss of this bone, the rule in all later reptiles, had begun even before the close of Carboniferous times.[1]

It may therefore be assumed with assurance that the ancestors of the pterosaurs had the phalangeal formula for the hand of 2, 3, 4, 5, 3, with the fifth finger much reduced in size and its supporting carpale 5 greatly reduced or entirely lost. In adaptation to aerial flight the pectoral girdle[2] and front limbs in the pterodactyls have been greatly modified throughout. In *Pteranodon* and *Nyctosaurus*, the most highly specialized, but three carpal bones remain, a proximal one, doubtless the fused radiale, intermedium, and ulnare; a lateral carpal for the support of the pteroid, which may be either the centrale or the first carpale; and a distal one, which in my opinion represents the fourth carpale alone; which, it will be seen, is the largest in reptiles. The carpale bearing the "Flugfinger" is always the larger; in *Pterodactylus* there is another, smaller one in front bearing the anterior metacarpals. I cannot believe that this carpale is the reduced or lost fifth carpale of the ancestral pterosaur carpus, nor that the wing-finger has migrated from its own vestigial carpale to the enlarged fourth while the fourth has migrated to a more anterior carpale. From the carpus then of pterodactyls it would seem highly probable that the carpale is the fourth and that it supports its proper finger the fourth, and not the fifth.

As has been known since the time of Cuvier, the phalangeal formula in pterodactyls, beginning with the first clawed finger, is

[1] I may mention here that evidence is accumulating to prove that the so-called Permian of Texas, or at least its lower part, and of New Mexico, as well as of Illinois, really pertains to the upper part of the Pennsylvanian.

[2] In my recent work on *American Permian Vertebrates*, p. 58, fourth line from bottom, occurs an unfortunate error, due to the omission of a qualifying phrase, "absent 'among nonamphibious reptiles,'" whereby I say that the supracoracoid foramen is wanting only among Pterosauria, when its absence in the Plesiosauria, most Ichthyosauria, Phytosauria, Chelonia is known to all.

2, 3, 4, 4, to which there are probably few or no exceptions. The first three of these agree absolutely with the normal and primitive formula of the first three digits. The fourth pterodactyl finger has

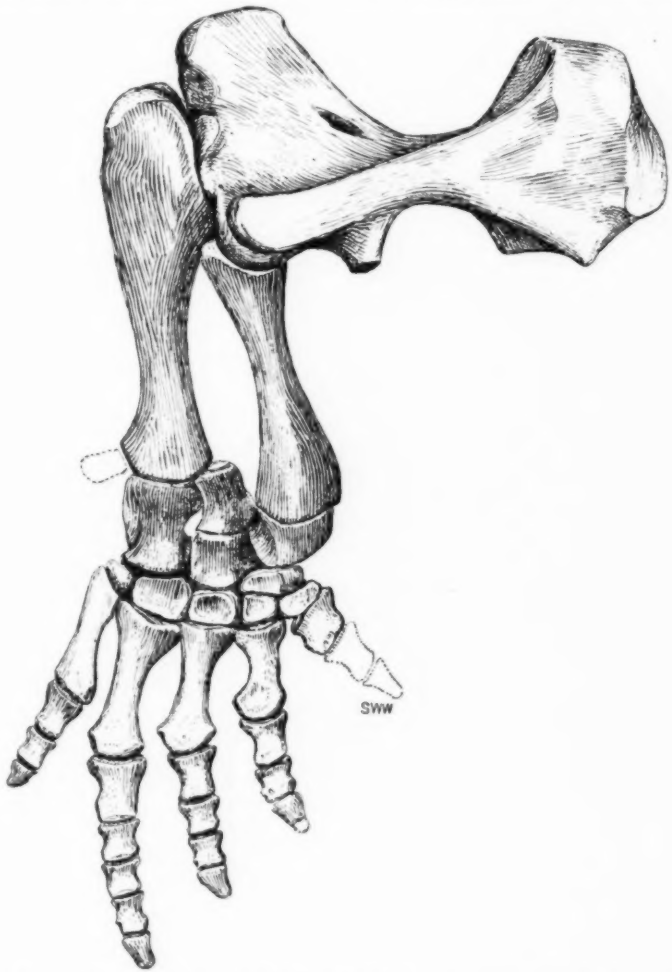

FIG. 3.—Right front leg of *Ophiacodon* Marsh, a theromorph reptile from the Permian of New Mexico. Two-thirds natural size.

but four phalanges, one less than the normal number, and quite that of the crocodiles; that is, as I have previously urged, it lacks the claw. In the acquirement of a membrane-bearing function this is precisely what would be expected in any finger, and is what occurs in the bats, as Abel has said. That the claw gradually elongated, changing its function from prehension to supporting, seems highly improbable. This finger then answers all the requirements for the fourth. If, on the other hand, in consonance with the Goldfuss theory, it is the fifth digit which acquired the membrane-supporting function, not only must the claw have changed its function and become elongated but a new phalange must have been added to the finger. Although among aquatic reptiles hyperphalangy is a common characteristic, we know of no instance among terrestrial vertebrates that I can recall where an additional phalange has been acquired, in either the front or the hind feet. And, if the Goldfuss theory be true, not only must there have been hyperphalangy in the fifth digit, but hypophalangy in the four preceding digits; that is, in the acquirement of a wing function, an increase and loss of phalanges must have occurred concurrently in the hand. I cannot believe that this was the case. Had we not to deal with the peculiar bone called the pteroid, articulating with the carpus and turned backward toward the elbow, the question of the homology of the wing-finger would doubtless never have been raised.

It is the pteroid, then, which has caused all the dispute, from the necessity of accounting for the bone, which, other than a misplaced first metacarpal, seems inexplicable. Two derivations have been imputed to it, as a sinew bone, and as a sesamoid bone. In favor of its being merely an ossified sinew is the fact that, in the remarkable specimen I have described of *Nyctosaurus*, seven well-ossified tendon bones are seen lying by the side of the forearm and hand, elongated bones with one end flattened and the other attenuated. In favor of the latter view that it is merely a sesamoid bone developed in the tendon of some carpal muscle originally is the fact that sesamoid bones do occur elsewhere in the pterodactyls. In the above-mentioned specimen of *Nyctosaurus* I found one lying over the end of the radius and another over the outer end of the coracoid; and I have seen them often in *Pteranodon*. Sesamoid bones have

bursal sacks and synovial joints. That the pteroid bone originated as a tendon or sesamoid bone is quite possible and even probable, but that the bone finally acquired another function, at least in the most highly developed forms, would seem to be very probable. The function that has generally been ascribed to it is that of a "Spannknochen" or tensor of the patagial membrane in front of the elbow. Under the assumed relations of the membrane to the front of the arm I have protested against this theory, since the fact is that there could have been little or no membrane in this region to be rendered tense, provided the membrane terminated, as is usually assumed, at the shoulder. Under the assumption that it really served as a "Spannknochen" I have suggested in an earlier paper that the membrane continued beyond the shoulder along the side of the neck to the skull.

In the accompanying restoration, Mr. Herrick E. Wilson, of the University of Chicago, after careful study, has embodied these views, based upon my skeletal restoration of *Nyctosaurus*. I believe that this restoration comes nearer to the real appearance of a pterodactyl

FIG. 4.—Right front leg of *Varanosaurus* Broili, a theromorph reptile from the Permian of Texas. Seven-tenths natural size.

in life than any that has hitherto been published. That the membrane extended on the neck is of course yet a hypothesis based upon the mode of development of the parachute in flying animals of today, and especially upon the structure of the pteroid bone and its relations to the forearm and shoulder. It is a fact that this bone seems to be better developed in *Nyctosaurus* than in other known pterodactyls, reaching by its pointed extremity pretty well toward the shoulder. If it was divaricated from the arm, as its perfect ball-and-socket mode of articulation with the carpus would indicate, and not inclosed in a muscle at its pointed extremity, its function as a supporter of a membrane in front of the elbow can scarcely be taken into consideration. With the membrane extending past the shoulder to the neck it would have had a distinct function as a "Spannknochen" and not otherwise.

Objection may be raised against the wide expanse of membrane between the legs. That the membrane extended to the tarsus on the peroneal side of the legs I think now hardly admits of doubt; the animals would hardly have been "flugfähig" were the legs wholly free, since the wing membrane would have been too narrow to serve as a parachute, and since the legs with their attached membrane must have functioned much like the tail feathers of modern birds in the control of flight. *Rhamphorhynchus gemmingi* has been restored by Zittel without membrane between the legs, but such a condition must seem impossible for such a flying creature. With the wings extended and the membrane connected with the ankles, there must have been a constant and considerable abducting strain on the legs, which must have required a constant muscular tension to withstand; and the legs, in the later pterodactyls at least, seem too frail for such tension. The head of mammals in the horizontal position is kept in place, not by muscular action, which would be unbearable, but by the elastic ligament of the neck. Something like this must have been necessary to withstand the constant abducting tension of the legs of pterodactyls in flight, and I assume that this was the function of a tense membrane between the legs, as well as that of directing flight. It has been suggested that the border of this membrane connected with the end of the vestigial tail; possibly that was the case, but, in *Nyctosaurus* at least, such

an excised membrane would have been little better than none at all.

That the ribs of the abdominal region extended out into the patagial membrane on the sides I have given reasons for elsewhere; I can see no other explanation for their position and lack of curvature in the specimen of *Nyctosaurus* to which I have referred.

THE TERRESTRIAL DEPOSITS OF OWENS VALLEY, CALIFORNIA

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CRITERIA FOR DISTINGUISHING ALLUVIAL FAN MATERIALS

INTRODUCTION

From September 9 to December 1, 1909, the writer in company with James A. Lane was in the southern half of Owens Valley, California, studying and mapping the general geology in a semi-detailed manner, and gathering data on the terrestrial deposits. The deposits studied particularly lie in the Mt. Whitney Quadrangle of the United States Geological Survey, though work was done in the Olancha Quadrangle, and beyond the limits of both these sheets, as problems demanded. The results of this work are used as a Doctor's thesis in the University of Chicago, this article being one chapter of that thesis.

The purpose of this paper is threefold: (1) to describe the characteristics of the terrestrial deposits of Owens Valley; (2) to discuss the causes and processes involved in their deposition; and (3) to deduce certain criteria whereby materials so deposited may be distinguished from other deposits such as those of lakes and seas, even after cementation has taken place. The adequate study of such deposits should lead to the establishment of criteria by which terrestrial deposits of earlier ages may with certainty be separated from marine deposits. It should also lead to the establishment of criteria for the recognition of various kinds of non-marine deposits. It is recognized that such criteria have already been discussed, and to a certain extent established. But many of these are applicable only to formations of pronounced characteristics, and there are yet many formations of one age and another whose origins are not yet established beyond doubt.

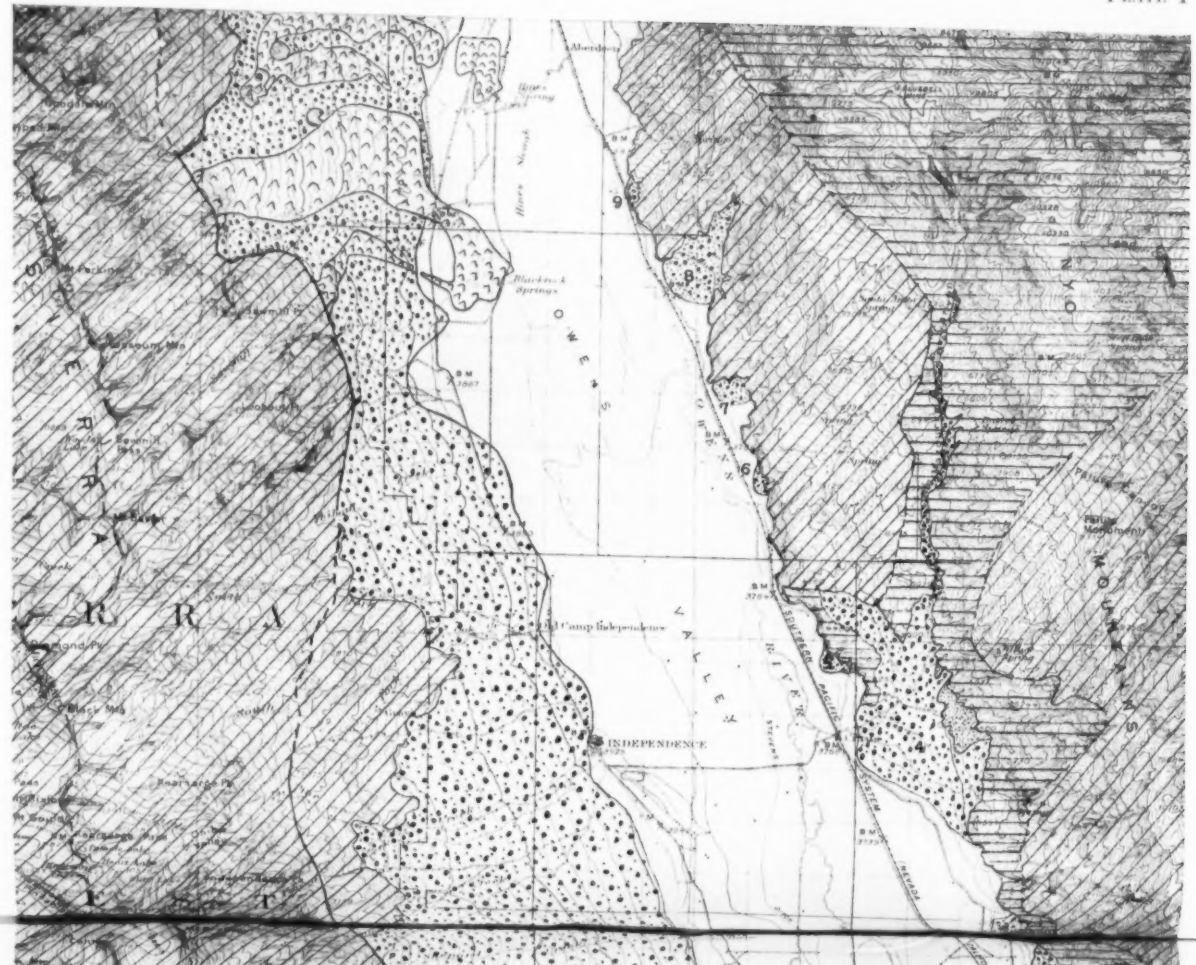
Owens Valley is an area about 100 miles long north and south, by 12–15 miles broad. It is situated in extreme eastern California, about east of a point on the coast midway between San Francisco and Los Angeles. The valley includes the villages of Bishop, Big Pine, Independence, Long Pine, and Keeler, which can be reached by the California and Nevada Narrow Gauge Railroad, connecting with the Southern Pacific at Mina, Nevada.

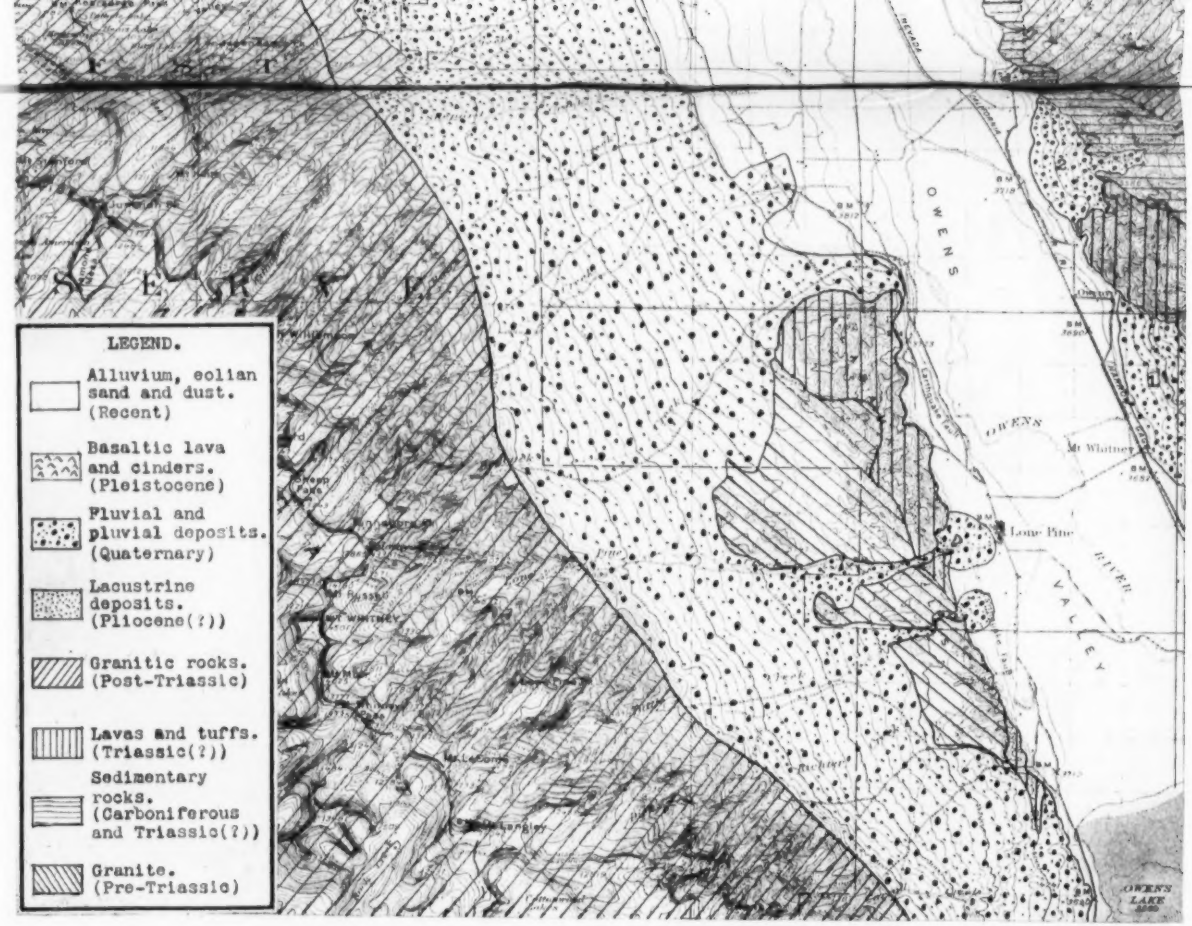
Physiographically, Owens Valley is located between the Great Basin on the east and the Sierra Nevada Mountain province on the west. The east wall of the valley is the west face of the Inyo Mountains, one of the semi-arid basin ranges, while the west valley

wall is the steep eastern slope of the Sierras. Owens Valley, between these two ranges, is occupied partially by Owens Lake, and drained by Owens River which flows into the north end of the lake. The surface of the valley is broken in several places by the Alabama Hills, Poverty Hills, and a series of recent volcanic cones and lava flows (see Plate I).

The eastern face of the Sierra Nevada Mountains is a precipitous fault scarp, probably of late Miocene age, attaining a height of 10,000 ft. above the bottom of Owens Valley. In this slope, streams and valley glaciers have carved numerous deep canyons, whose lower portions are choked with drift and whose upper portions are the cirques and bare surfaces of glacially eroded regions. The rock of the mountains in this region is massive, coarse-grained igneous rock, chiefly granite. This rock is weathered chiefly by mechanical processes. Temperature changes and the wedge work of ice cause pieces of rock varying in size from a fraction of an inch to a score or more of feet in diameter to break off and roll down the steep slopes, each piece being broken or worn smaller as it goes. Plants, animals, and ground water are relatively unimportant as weathering agents here, because by reason of the steep slopes, they are not present in abundance. On the other hand, because of these steep slopes, gravity is more than usually important. Oxidation, hydration, carbonation, solution, etc., as usually performed by atmosphere and ground water, do not take place sufficiently rapidly to produce great results on the rocks before these last are disrupted and taken away. That is, the mechanical processes of weathering and transportation take place more rapidly than the chemical processes, and the result is arkose material carried down the mountain canyons and deposited in the valley below. These are the materials to be described as the terrestrial deposits of the valley.

Unlike the Sierras, the Inyo Mountains contain both igneous and sedimentary rock, in about equal abundance. Ordovician, Carboniferous, and Triassic sedimentary formations have been interbedded with Triassic lavas, and intruded by Cretaceous granite and diorite. Though these mountains are not so high by 4,000 ft. as the Sierras, and the slopes are not so steep, still here also mechanical processes of weathering keep ahead of chemical


INDEPENDENCE
OWENS VALLEY
OWENS RIVER
SIERRA NEVADA
INYO MOUNTAINS
Blackrock Springs
Aberdeen
Camp Independence
Mt. Langley
Mt. Whitney
Mt. Williamson
Mt. Tyndall
Mt. Barcroft
Mt. Baxter
Mt. Goddard
Mt. Darwin
Mt. Mendel
Mt. Humphreys
Mt. Emerson
Mt. Morgan
Mt. Gayley
Mt. Agassiz
Mt. Abbot
Mt. Dade
Mt. Bolton Brown
Mt. Haeckel
Mt. Gilbert
Mt. Dana
Mt. Lyell
Mt. Maclure
Mt. Ritter
Mt. Banner
Mt. Lamarck
Mt. Crocker
Mt. Wallace
Mt. Hilgard
Mt. Warlow
Mt. Perkins
Mt. Basin
Mt. Bonnie
Mt. Tom
Mt. Williams
Mt. Langley
Mt. Whitney
Mt. Barnard
Mt. Pinchot
Mt. Kaweah
Mt. Brewer
Mt. Stanford
Mt. Clarence King
Mt. Cotter
Mt. Gardiner
Mt. Silliman
Mt. Whitney
Mt. Langley
Mt. Barnard
Mt. Pinchot
Mt. Kaweah
Mt. Brewer
Mt. Stanford
Mt. Clarence King
Mt. Cotter
Mt. Gardiner
Mt. Silliman



FROM MT. WHITNEY, CAL., QUADRANGLE

Scale, about three miles to the inch. Contour interval, 100 feet

processes, this being due partly at least to the fact that the Inyo Mountains receive little precipitation, and the moisture necessary for chemical processes is lacking. Here also canyons have been cut by streams, and material has been transported to the valley and deposited, but unlike those of the Sierras these streams are intermittent, and carry material only after the infrequent rains. The Inyo Mountains have not been glaciated.

The deposits considered in this paper occur along the east foot of the Sierra Mountains on the west side of the valley, and discontinuously along the west front of the Inyo Mountains, which border the valley on the east. The phenomena on the opposite sides of the valley are sufficiently unlike to warrant description separately.

DEPOSITS AT THE BASE OF THE SIERRA MOUNTAINS

LOCATION AND EXTENT

Within the area of the Mt. Whitney Quadrangle, terrestrial deposits at the east base of the Sierra Nevada Mountains cover a belt 1–7 miles wide. In the Olancha Quadrangle to the south, corresponding deposits extend for many miles in a narrow and more or less disconnected belt.

At the north, the plain of the terrestrial deposits is overlain by recent lavas and volcanic cones. Northwest of Owens Lake the alluvial deposits lie against the west edge of the Alabama Hills, and extend around the north and south ends. Two narrow continuations of the deposit extend through gaps in these hills, and deploy slightly on the east side. Elsewhere the plain joins the flat bottom of Owens Valley along a more or less distinct line. On the west side the plain is limited sharply by the foot of the mountains.

In the aggregate, the deposits cover about 175 square miles in the Mt. Whitney and Olancha quadrangles.

TOPOGRAPHY

FANS AND INTER-FAN AREAS

Topographically, this plain of pluvial and fluvial deposits takes the form of a series of fans joined together at their lateral edges. At first glance, either in the field or upon the topographic maps,

it seems to be a continuous plain sloping from the mountains; but studied in detail, it resolves itself into low, gently sloping fans separated by broad, ill-defined, shallow depressions. The fans deploy and become less distinct at a distance from the mountains; the depressions are therefore broader, deeper, and better defined close to the mountains. At its outer edge, the topography of the deposits approaches a plain, in which neither fans nor inter-fan areas can be distinguished.

The axes of the fans are on lines which are continuations of canyons in the mountains; the depressions are between the mouths of the canyons.

From Owens Lake north, the following fans can be distinguished: those of Richter, Tuttle, Lone Pine, Hogback, George, Bairs, Shepard, Pinyon-Pine, Oak, Thibaut, and Sawmill creeks. The last three are small though sharply defined.

A few notes taken north of Lone Pine Creek are here copied, in so far as they refer to the topography of the fans:

> The fan opposite Lone Pine Canyon is sharply set off from the fan of Hogback Creek to the north. Beginning at the mouth of the canyon, it spreads promptly to the north, a distance of about half a mile at the immediate foot of the mountains, and one and one-half miles within a distance of a mile from the mountains. Farther from the mountains, it joins the fans on either side, and its distinctness is there lost. Its north edge is fairly distinct for two miles from the mountains, being markedly higher than the broad, irregular, linear depression between it and the fan of Hogback Creek. This depression is distinct near the mountains, but becomes gradually shallower and narrower away from the mountains, until the two fans coalesce two miles or so out. . . . . From the depression, the slope of the fan of Hogback Creek shows a distinct rise. . . . . The south side of the fan of Shepard Creek is not especially well developed, though it is set off distinctly from the fan to the south. The depression between these two fans is about 200 ft. below their tops, and is one-fourth to one-half a mile broad. . . . . North of the fan of Shepard Creek, the surface declines and does not again reach the high level of this fan as far as the alluvium can be seen.

The streams have a distinct tendency to leave their fans for the depressions between. Shepard Creek now flows in the depression south of its fan. The North Fork and South Fork of Oak Creek have joined in the depression between their respective fans. At some time they were undoubtedly parallel streams. The photo-

graph (Fig. 1) shows the two fans, South Fork flowing in the low place, and North Fork leaving its fan for the depression. This shifting of streams to the inter-fan areas is suggested as a common and efficient process in the tying together of fans, making piedmont alluvial plains, or *bajadas*.[1] By this shifting, fans are made between fans, tying them together and tending toward the union of the fans into one plain.

CHANNELS AND RIDGES

Low ridges and shallow depressions on the individual fans constitute topographic features of a second order. These are the

FIG. 1.—A photograph of the fans of Oak Creek, showing South Fork (*ab*) flowing in the inter-fan depression, and North Fork (*cd*) leaving the fan to join South Fork in the depression.

channels and depositional features of the streams which deposited the fans. The depressions are more noticeable than the ridges.

The depressions are, as a rule, about 10 ft. deep and less than 100 ft. across, though at a maximum they reach a depth of 20–25 ft. and a width of quite 100 ft. Their bottoms are usually flat and their slopes as steep as the material will permit. The elevations are less numerous than the depressions, and have less relief. They are seldom more than 5 ft. above the surrounding plain, and their height in many cases is only equal to the diameter of the individual bowlders of which the ridges are composed. The ridges consist

[1] The term *bajada* has been suggested by C. F. Tolman (*Jour. Geol.*, XVII [1909], 141) to replace the longer term commonly in use. It has the advantage of brevity, but lacks the explanatory value of the older term.

of mere divides between channels and of lines of bowlders bordering the channels.

In keeping with their origin, the depressions and ridges are radiate in their arrangement. At the head of each fan, these features are few; toward the outer edge they are numerous; but at the extreme edge they are again rare. Three miles from the edge there are probably 50 channels, for one close to the head, and something like that proportion between the same three miles from the edge and the outer edge itself. Channels which, near the head of the fan, are close together, diverge outward, and each may break up into other channels, each less deep and less broad than the one from which it springs. Quite commonly these channels lead to depressions between fans and disappear.

It is clear that these channels on the fans mark the courses of the distributaries from the fan-making streams. The streams branched again and again, some of the distributaries reaching the inter-fan depressions and flowing off through them. It is equally clear that some of the elevations are merely inter-distributary divides. The origin of the ridges bordering the depressions is not so clear. Possibly they are in principle natural levees, built as the waters overflowed their channels. It is understood that these are the streams which deposited last on the surface of the fans. In the building of the bajada, the channels undoubtedly shifted frequently, those of one time being filled up and a new set formed during periods of greater deposition following heavy rains or the rapid melting of snow in the mountains.

THE STREAM CANYONS

The streams of the bajada do not now distribute over the fans, but flow in deep, steep-sided, canyon-like valleys; that is, the bajada is being dissected (Fig. 2). This is true to a greater or less extent of all the streams which have played a part in the deposition of the plain.

The canyons in the bajada vary in depth from 20 ft. to 250 ft., and average about 200 ft. in width. The depth is determined by the size of the stream, the height of the fan, and the position of the stream on the fan. The most pronounced canyons are those of

Carroll and Lone Pine creeks, which are large streams flowing in the high central part of well-developed fans. Carroll Creek canyon is 250 ft. deep at the head of the fan, and shallows to less than 50 ft. at the edge of the bajada. Shepard Creek is almost as large as either of the two streams previously mentioned, but it flows on the side of its fan, where the surface and gradient are lower, and its canyon is only 30 ft. deep. Hogback Creek has cut deeply at the head of its fan, but farther out, where the stream has shifted to the side, there is little intrenchment.

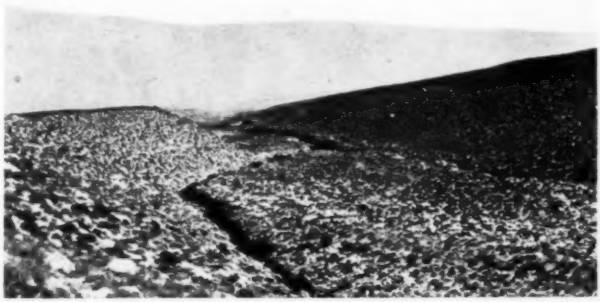


FIG. 2.—The canyon of Carroll Creek in the Sierra bajada. The dark strip consists of trees 20 ft. high.

These canyons are the most conspicuous topographic features of the bajada. They clearly follow the building of the bajada, and were excavated under different conditions. They therefore have both an expository and a historical value. Problems connected with them will be discussed later.

BOWLDER BELTS

A fourth topographic feature of the bajada consists of almost innumerable lines of bowlders which, though primarily a matter of the constitution of the bajada, affect the topography in a minor way.

These lines of bowlders have a radiate arrangement similar to that of the channels and ridges. The bowlders are so close together

as to make low and discontinuous ridges, which by winding his way among the bowlders one may in some instances be able to cross without climbing. The height of the ridges is determined by the size of the bowlders, and is usually less than 10 ft. They seldom consist of more than two thicknesses of bowlders.

THE SLOPE OF THE BAJADA

The slope of the piedmont plain away from the mountains varies rather uniformly with distance from the mountains. It also varies

FIG. 3.—The slope of the Sierra bajada as seen on the north wall of the canyon of Carroll Creek.

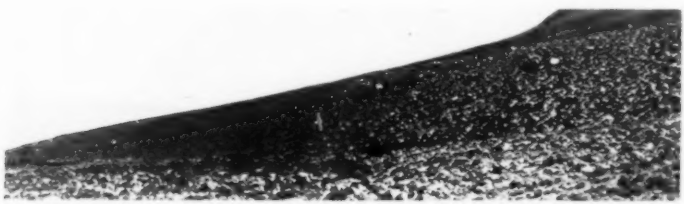


FIG. 4.—The slope of the Sierra bajada on the south wall of the canyon of Carroll Creek.

irregularly from place to place along the foot of the mountains. Along Carroll Creek the slope at the face of the mountain is 18° and 20° (Figs. 3 and 4). Where it is 20°, the angle decreases to about 12° a quarter of a mile from the mountains; and where it is 18° at the mountains, the slope is 6–8° a mile or so out. The fan of Lone Pine Creek has a slope of 6° at the mountains, which decreases almost uniformly to a very low slope at the west edge of the Alabama Hills. The difference between the slopes of the fans of Lone Pine Creek and Carroll Creek might be due to a diastrophic tilting, which either did not occur at Lone Pine Creek or did not

affect the fan there. However, no other evidence of diastrophism appears at Carroll Creek. Probably the difference is due to variations in the gradient and size of the two streams in the mountain canyons, at the time the fans were built. The *average* slope of the fans in the valley at the base of the mountains is about that of the fan of Lone Pine Creek, 6°. The slope is greater along the axes of the fans than in the inter-fan depressions.

MATERIALS

The material of the Sierra bajada is not well exposed, but some idea of its upper portion can be obtained. Nothing is known of

FIG. 5.—The largest bowlder seen in the Sierra bajada. The man is 6 ft. tall. This bowlder lies in the yard of the Cerro Gordo power shanty in Lone Pine Canyon, 1½ miles from the foot of the mountains.

that portion lower than 300 ft. from the surface, as there are no cuts so deep, and well-records are lacking. The material may be seen in three sets of places: (1) on the unaltered surface of the plain, (2) on the sides of the shallow channels, and (3) in the walls of the canyons.

Lithologically, the bajada is composed of material from the granitic rocks of the Sierras, disintegrated rather than decomposed. Its components are bits of granite, rather than crystals of quartz or feldspar. Even the disintegration is not complete, for the material is commonly coarse. It is clear that the source of the material is the mountains, and that it was removed from the parent ledges mechanically, and transported to its present position by streams,

aided in the upper parts of the canyons by glaciers. There is every evidence of immature weathering of the materials. At the time the fans were being deposited, the mechanical processes of weathering greatly exceeded the chemical, and transportation was free and rapid.

TEXTURE

The fans contain all textural grades from pieces the size of small sand grains and even clay particles, to bowlders more than 20 ft. in diameter, but pieces less than an inch in diameter predominate.

The most striking and surprising feature of these fans is the extreme coarseness of *some* of its materials. Innumerable large

FIG. 6.—Bowlders on the surface of the Sierra bajada. Their size may be estimated from the horse. Picture taken on the fan of Sawmill Creek about a mile from the foot of the mountains.

and small bowlders appear on its surface, on the sides of the shallow channels, and on the walls and floors of the canyons. On the unaltered surface, they occur in radiating lines and belts, roughly parallel with the radiating channels. They are practically confined to the higher parts of the surface, where the main streams flowed. None appears in the inter-fan depressions. More bowlders are scattered near the heads of the fans than toward the outer edges but they are not noticeably larger here. They are arranged in belts or low ridges along the borders of the shallow channels and are scattered more sparsely on the side slopes. Bowlders are numerous on the walls and bottoms of the canyons, but without definite arrangement. The beds of the streams are everywhere choked with them, and they occur in and along the braided channels

used by the streams in time of flood. Their unusual abundance in the canyons is doubtless due to the bowlders having been sorted out in the process of canyon-cutting, the finer material being carried on and the coarse left.

The whole surface of the bajada considered, the average diameter of the bowlders is perhaps about 2 ft. but those 8 ft. in diameter are by no means uncommon. The largest seen are a mile west of Lone Pine, 6 miles from the mountains, and at the Cerro Gordo power shanty, on Lone Pine Creek, $1\frac{1}{2}$ miles from the mountains.

FIG. 7.—The canyon of Lone Pine Creek in the Sierra bajada. Bowlders appear almost as large as the two-story house.

The one west of Lone Pine is $10\times20\times30$ ft. above ground. The size of the one at the shanty is shown in Fig. 5, the man being 6 ft. tall. With these exceptional bowlders are thousands of others as large as 10 ft. in diameter, as can be seen from Fig. 7. The size and distribution of this coarse material may be seen further in Figs. 6 and 7. Fine material in the bajada is shown in Fig. 8.

STRUCTURE

Owing to the scarcity of good exposures, the structure of the materials of the Sierra bajada is not readily determined. The only satisfactory exposure is near the mountains on Lone Pine Creek (Fig. 9). Because the canyon walls never stand in vertical bases, but slump down readily to gentle slopes, they show the

texture only, not the structure. The relations of coarse and fine material can be seen to some extent on the surface of the plain.

As has been shown above, the coarse and fine materials are more or less separated on the surface of the plain. There are considerable stretches, usually the lower areas, where the surface material is all fine. Such areas are interrupted by narrow belts of large bowlders. If the structure of the whole plain were judged by its

FIG. 8.—Fine material in the Sierra bajada seven miles from the mountains

surficial aspect, the material could be known to be roughly sorted into many narrow radiating belts of coarse materials, and broader belts of fine materials. Presumably these lines would not have the same position horizontally for any considerable vertical section, as the stream channels undoubtedly shifted and distributed often.

So far as cuts in the bajada show, the materials consist of a mixture of large blocks of granite, bowlders not so large, angular fragments the size of cobbles, tiny angular bits of rock, sand, and clay. Where any considerable vertical section is seen, these different grades are sorted into indefinite lenses and pockets. There are no definite layers of great extent. Divisions of material are nowhere seen to be continuous for as much as 100 ft. Some small

exposures show material which is apparently unstratified. Even where sorted into lenses or irregular areas, there is a considerable mixture of all sorts of material in each division, each merely averaging a little coarser or a little finer than its surroundings.

All materials are clearly water laid, but under conditions which allowed of very poor sorting.

The structure and texture of the materials are brought out best by detailed descriptions and photographs. Such illustrations are given below and in Figs. 9, 10, 11, 12, and 13.

FIG. 9.—A section in the Sierra bajada from the south wall of Lone Pine Canyon, ½ mile west of the Cerro Gordo power shanty.

1. Two hundred to three hundred yards above the power shanty on the south wall of the valley of Lone Pine Creek, wash and gravity have exposed the material almost continuously for a distance of about 100 ft. vertically. The section consists of both fine and coarse material roughly separated from one another. There are two horizons of coarse bowlders, one 20 ft. from the top and the other about 30 ft. from the bottom. In the upper horizon the bowlders are fairly well rounded, and range up to 4 ft. in diameter, the average being about 1 ft. In the lower zone of bowlders there is greater range in size. There are numerous pieces 6 in. through, and several 6 ft. or so in diameter. The sorting is very slight. Between these two horizons the materials are mostly fine, though large bowlders are not entirely absent. Immediately above the

lower zone of bowlders is a fairly well-defined bed of gravel, the constituents of which average 3–4 in. in diameter. Between this gravel layer and the upper zone of bowlders, the material differs in different parts of the cut, the structure being decidedly pockety. In one place the fine gravels grade into the coarse bowlders above; in another, there is a body of clay between the two; in another, the gravel layer does not appear, and clay separates the two beds of bowlders (Fig. 9).

2. A six-foot cut a mile from the mountains shows a matrix of clay and sand in which there are angular fragments averaging

FIG. 10.—Roughly sorted materials of the Sierra bajada on George Creek

10 in. through, with occasional bowlders 3 ft. in diameter. The bowlders are angular or subangular, and none are well rounded. They are not abundant enough to touch one another. There is apparently no sorting.

3. A hundred yards above the last section, the material is rudely but distinctly sorted. At the bottom there is a fairly uniform layer of angular gravel, averaging 4 ft. in thickness, of which the upper $1\frac{1}{2}$ ft. give place at the east end to a projection downward of a pocket from the coarse layer above. There is little clay in the cut, and the fragments of rock are abundant enough to touch one another. The pores are filled with coarse, arkose sand, loosely packed.

4. The last section gives place, within a few feet, to unsorted material entirely similar to that of section 2. From here to the mountains the sorted and unsorted materials occur with about

equal frequency, in the same position relative to the stream and to the surface of the fan.

5. Material is exposed on the Mt. Whitney trail through the Alabama Hills. It is composed of rounded or partly rounded granitic bowlders, up to a foot in diameter, with a sparse matrix of granitic pebbles. Though stratification is not apparent, all material is clearly water laid (Fig. 12).

6. On Dietz Creek, just above its junction with Tuttle Creek, material is exposed. It is a mixture of very fine angular fragments

FIG. 11.—Unstratified material on George Creek. This section occurs within only a few feet of that shown in Fig. 10.

with material having the texture of coarse sand. The fragments are not so angular as pieces just broken by weathering. They seldom exceed a half-inch in diameter, and the average is about $\frac{1}{16}$ of an inch. The finer material consists of arkose, flakes of mica, grains of pyrite, and of ferro-magnesian minerals, being almost as common as quartz. The coarse and fine materials are unassorted.

From these descriptions and photographs, the following characteristics of the materials are shown:

1. The material was derived from the rock of the Sierra Nevada Mountains.

2. It is the result of immature weathering in the mountains.

3. In texture the materials range from clay-like particles, to bowlders 30 ft. in diameter.

4. Some of the large bowlders are ice-shaped, and some have been shaped slightly by water.

5. Stratified, partly stratified, and entirely unassorted materials occur in something like equal proportions.

6. Where stratification exists, the materials are sorted into lenses and pockets, never into uniform, continuous layers.

FIG. 12.—A pocket of stratified gravel in the Sierra bajada seven miles from the mountains on Lone Pine Creek.

7. The materials become gradually finer as distance from the mountains becomes greater, at least so far as sub-surface material is concerned.

8. No fossils were found in the material.

These features will be discussed after the deposits at the foot of the Inyo Mountains have been described.

TERRESTRIAL DEPOSITS OF THE INYO MOUNTAINS

Terrestrial deposits are represented in the Inyo Mountains by two distinct types of materials of two distinct ages. They will therefore be discussed separately.

PLIOCENE LACUSTRINE DEPOSITS

No description of the terrestrial deposits of Owens Valley, and no discussion of the older deposits at the foot of the Inyo Mountains would be adequate without mention of certain lacustrine clays and

sands in Waucobi Canyon, described by Walcott,[1] and in the vicinity of Haiwee described by Turner,[2] Fairbanks,[3] and Campbell,[4] even though such mention leads beyond the confines of the Inyo Mountains. Both these deposits were seen by the writer, and they are here discussed in so far as they may be used as a type of lacustrine deposits. Walcott[5] and Spurr[6] have interpreted these deposits in slightly different ways, but both agree that they are lake deposits, and as such they will be described. Discussion as to whether they record great recent uplift of the Inyo Mountains, as according to

FIG. 13.—Unsorted material of the Sierra bajada

Walcott, or were deposited in a deep, widely distributed lake, as Spurr contends, is not in place here, though such discussion is given in the unpublished part of the thesis.

LAKE BEDS IN WAUCOBI CANYON

Waucobi Canyon, or the Waucobi embayment as it is called by Walcott, is a re-entrant in the west face of the Inyo Mountains a few miles north of the boundary of the Mt. Whitney Quadrangle

[1] C. D. Walcott, *Jour. Geol.*, V, 240–48.

[2] Personal communication to Spurr.

[3] H. W. Fairbanks, *Am. Geol.*, XVII, 69.

[4] M. R. Campbell, *Bull. U.S. Geol. Surv. No. 200*, p. 20.

[5] *Jour. Geol.* V, 344–48.

[6] J. E. Spurr, *Bull. U.S. Geol. Surv. No. 208*, pp. 209–10.

east of Alvord. In this re-entrant are a series of unconsolidated and partly consolidated sands, clays, and gravels. They were traced from wall to wall of the re-entrant, and up the canyon for some $3\frac{1}{2}$ miles. Mr. Walcott reports their continuation almost to the crest of the mountains.

There are two more or less distinct phases of this deposit. Near the north and south walls of the re-entrant are interbedded clays, limestones, and conglomerates. These materials are mostly sorted into distinct beds, but are locally arranged in pockets or irregular

FIG. 14.—Lacustrine limestones and conglomerates, deposited near shore in the Waucobi embayment.

areas, when seen in sections. Two miles east by northeast of Alvord, a ledge of limestone and conglomerate outcrops under a low hill of angular alluvium. The limestone is white, porous, earthy, and filled with small fossils of gastropods. Other rock has a matrix of calcium carbonate, but contains enough pebbles to make it conglomeratic, though the pebbles are seldom in contact. The stony matter is fairly well rounded. In size its pieces reach 6 in. in diameter, though the average is about 1 in. The pebbles are mostly of sedimentary rock, but with some granites. All the material is local.

A series of exposures along the main road $1\frac{1}{2}$ miles southeast of the fruit ranch of J. S. Graham, at the southeast margin of the re-entrant, shows well the constitution of the beds. All the material is irregularly sorted. In some places it is of light-yellowish

clay, which contains enough lenses and pockets to give it a bedded aspect. In other places it is made up of alternating layers of gravel and clay, the latter containing bowlders in many places (Fig. 14).

Just below these coarse, roughly sorted materials on the main road, the constitution changes abruptly to sandy clay, arranged in continuous, uniform, apparently horizontal layers. The change from coarse, poorly sorted conglomerates to fine clays takes place within 500 ft. These clays appear all the way to the mouth of the

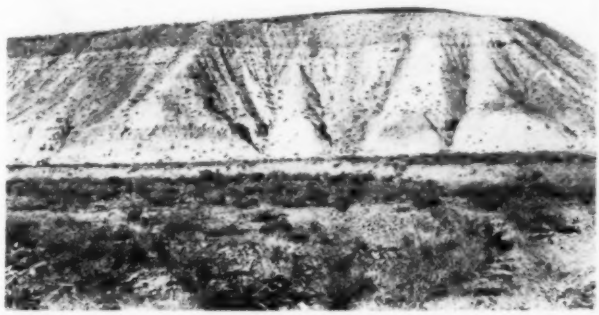


FIG. 15.—Lacustrine sand and clay in the Waucobi embayment. The layers are continuous and of uniform thickness.

canyon, as erosional hills about 100 ft. high, and in the valley walls. Most of the clay is fine, becoming white dust when powdered. Some layers are sandy and some calcareous. They are not usually firmly cemented. Layers 1–10 ft. in thickness can be traced continuously along the hills (Fig. 15).

These are doubtless lake deposits, the coarser marginal conglomerates being the littoral phase, and the centrally located clays and sands having been deposited in quieter, deeper water, farther from shore. The fossils have been determined by Dr. Dall as Pliocene to recent. As the beds lie unconformably under Quaternary alluvium, they are probably Pliocene or early Quaternary in age.

LAKE BEDS NEAR HAIWEE

Toward the south end of Owens Valley, in the vicinity of Haiwee post-office, there is a series of calcareous and arenaceous lake beds. They were seen by the writer $\frac{1}{2}$ mile southwest, 1 mile east, and $\frac{3}{4}$ mile northwest of the post-office. They are fine, white, and distinctly bedded. East of the post-office, the beds dip 8° to the northwest. Northwest of the post-office they dip 14° north. They were best seen $\frac{3}{4}$ mile northwest of the post-office, where a hill 175 ft. exposes them from top to bottom. They consist of light-colored, siliceous

FIG. 16.—Unconformity between Quaternary conglomerates and Pliocene lake beds north of Haiwee. Some of the bowlders of the conglomerate are composed of the underlying clays.

fine clays or shales. In the lower part of the exposure numerous small flat bodies of gypsum occur. Most of the plates lie parallel with the beds, but in some places they appear as secondary bodies along joints and faults.

The lake beds here are covered with a hard, coarse conglomerate derived from the Coso Mountains to the east. The lake beds and conglomerates are unconformable. The conglomerate lies on the very irregular surface of the truncated edges of the dipping beds of clay, the surface between the two having a relief of about 15 ft. (Fig. 16). The constituents of the conglomerate are chiefly granite, sedimentary rock, and scoriaceous basalt, but near the contact many large fragments of the underlying clays are also included. The

conglomerates must be as old as the early Quaternary. The hill on which they occur is far from the Coso Mountains and separated from them by numerous valleys, similar hills, and more lake beds. The lake beds are then pre-Quaternary, probably Pliocene, and correlated with the similar beds in Waucobi Canyon. No fossils were found here.

OLDER DEPOSITS AT THE FOOT OF THE INYO MOUNTAINS

Bearing in mind the main characteristics of the deposits described above, and accepting the idea of their lacustrine origin, as we are apparently forced to do, we can proceed to a description

FIG. 17.—Low hills of old deposits surrounded by present-day fans, northeast of Mt. Whitney station.

and interpretation of the older deposits of terrestrial material at disconnected points along the foot of the Inyo Mountains.

Distribution as indication of age.—At several places, most notably northeast of Mt. Whitney station and east of Citrus, hills of terrestrial material rise 100 ft. above fans which are now in process of making about them. The materials of the hills differ from those of the fans in texture, and in the fact that they are cemented.

Along the west face of the mountains immediately northeast of Mt. Whitney station, an exceptional series of events is recorded by the nature and relations of the alluvial deposits. Two hills, 100 ft. or more in height, occur half a mile apart, and half a mile from the foot of the mountains. Between and around these hills the lower surface is covered with the typical alluvium of the region. The hills themselves are of gravel and sand. Evidently a great

deposit was laid down here, its remnants being represented by the hills. Conditions changed so that erosion took place, the old deposit being dissected into hills and valleys. Later, as the streams were brought to adjustment again, they deposited new fans among the remnants of the old deposit (Fig. 17).

Due east of Citrus, a series of low spurs projects from the foot of the mountains into Owens Valley. At the foot of the mountains they stand 50–75 ft. above the plain, and become gradually lower westward. They are not in direct contact with the present fans, though fans occur at lower levels north and south of them. These projections are not at the mouths of present canyons (Figs. 18 and 19).

FIG. 18.—Lacustrine beds (light colored) lying against rocks of the Inyo Mountains (darker rock to the right), east of Citrus. Stratification may be seen in the left center.

The deposits in Mazourka Canyon, the canyon east of Aberdeen, and on the flanks of the mountains east of Keeler should also be included in this category. In the two canyons, older cemented gravels occur as distinct, flat-topped, but eroded terraces, 50 ft. above the stream beds. East of Keeler, hills of conglomerate rise 200 ft. above present alluvial surfaces.

Constitution.—The materials of the older deposit at the foot of the Inyos differ from those of the Sierra bajada in various ways; especially in (1) lithological composition, (2) texture and shape of pieces, (3) structure, (4) cementation.

1. This deposit is made up of fragments of all rocks occurring in the Inyo Mountains, from which they are derived, including both igneous and sedimentary rocks.

2. The constituents have not a great range in size. In place of large bowlders, the coarser materials are large-sized cobbles or very small bowlders. Texturally, the fine material is sand or clay. The average size of particles is probably less than half an inch in diameter. Bowlders even as large as 1 ft. in diameter are wanting.

In the Sierra bajada the pieces of rock are either ice-shaped, or they are almost as angular as when broken off by weathering. Here the effects of glaciation are not seen. The fragments have been worn to pebbles, few sharp or irregular edges appearing.

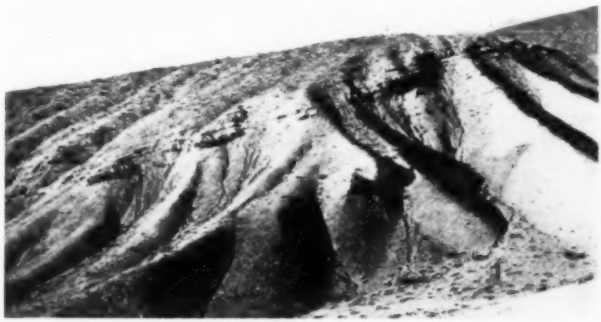


FIG. 19.—Close view of the older deposits east of Citrus. Note the layered structure and the dip of the beds.

They are in general well rounded, having been shaped by the action of water.

3. These materials are arranged in definite, continuous layers of gravel and sand. The layers can be traced the whole length of the various outcrops as beds of nearly uniform thickness. East of Citrus a definite, continuous layer of clean, fine gravel, uniformly 2 ft. thick, overlies a layer which is a mixture of small angular fragments, sand, and clay. Northeast of Mt. Whitney station the talus from a deep cut is of uniform-sized cobbles and sand. The stratification of this material may be seen in Figs. 18 and 19.

Wherever exposures were seen east of Citrus, the beds have an appreciable westward dip (away from the mountains). Clinometer readings vary between 8° and 18°. The *direction* of dip is nearly

constant. No faults, minor folds, or other evidences of diastrophism were seen. This dip may be depositional, or the beds may have been tilted to their present position by an uplift in the mountains. Eighteen degrees is a high dip to be considered depositional when the material is fine.

4. The older deposit shows a tendency toward cementation, and some layers are firmly cemented. In general it is the layers of coarse material, originally more porous, that are cemented.

In the beds east of Citrus mentioned under (3) above, the upper layer of gravel is cemented to firm conglomerate. It is so solid as to ring under the hammer and to need more than one hard stroke

FIG. 20.—A stream terrace of older alluvium in Mazourka Canyon

before it is broken. The material of the finer layer below cannot be picked out by the hand, but yields readily to the hammer. The gravel layers are almost everywhere so indurated that they stand out conspicuously, the determination of dips thus being made easy.

The above characteristics hold for all the deposits of older materials at the foot of the mountains, with the exception of those in Mazourka Canyon. The deposits in this canyon belong to the older deposit, for they occur in terraces above the present depositional surfaces, but the materials are in some respects different. Areally considered they take the form of the canyon in which they were deposited, and thus occur in a long strip. They constitute more or less definite stream terraces on the sides of the present valley (Fig. 20). Texturally they are like the deposits along the foot of the mountains, the chief difference being in the strati-

fication. Instead of being in definite layers, as are the deposits at the foot of the mountains, the materials in the canyon are in indefinite lenses and pockets, similar to those of the Sierra bajada, though on a much smaller scale.

An examination of two detailed sections noted just above Barrell Springs brings out the difference between these deposits and those east of Citrus and Mt. Whitney station:

1.

1½ ft..... Angular fragments the size of cobble, and clay.
1 ft..... Well-sorted, very fine gravel. Pinches out in both directions.
1½ ft..... Mixture of cobbles and clay. Pinches out upstream.
1½ ft..... Clay with some small angular bits of rock.
1 ft..... Well-sorted, loose, fairly well-rounded cobbles; average size 1½ in.; one-inch clay layer in middle.
3 ft..... Mixture of sand, clay, and gravel; little or no stratification; pockety; contains one bowlder one foot in diameter.
2½ ft..... Clay, sand, some gravel; poorly sorted.
2½ ft..... Fine angular fragments; little or no clay or sand; well assorted.

2. Fifty feet down the valley from the last, the following section occurs:

3 ft..... Mixture of coarse and fine angular gravel, with clay in the interstices; average size of constituents 1 in. in diameter; occasional bowlders 1 ft. in diameter.
1 ft..... Moderately fine gravel; little or no clay; no pieces larger than 3 in. in diameter; pinches out in 12 ft. up valley.
2 ft..... Clay and pebbles intermixed; rude layer of cobbles in middle.
2½ ft..... Fairly well-sorted gravel, coarser at bottom. Pinches out rapidly in both directions. Loosely packed, interstices not filled.
3 ft..... Irregularly bedded bowlders, cobbles, fine gravel, clay.
2 ft..... Indefinitely bedded fine angular gravel. Average ½ in. in diameter.
1 ft..... Pockety, coarse gravel, constituents up to 10 in. in diameter.

In both sections, the materials are slightly cemented. Not a single subdivision of one could be traced 50 ft. to the other. For further details of these materials see Figs. 21 and 22.

It is thus seen that the materials of Mazourka Canyon differ from the rest of the older deposit at the foot of the mountains in

that it includes coarser materials and has a lens and pocket structure (cf. Figs. 19 and 21).

Origin of the older deposit at the foot of the Inyos.—It will be seen from the foregoing that most of the older deposit is sufficiently unlike the Sierra bajada to lead one to conclude that its mode or conditions of origin were not the same. On the other hand, if it be compared with the near-shore phase of the lake beds in Waucobi Canyon, a strong resemblance will be seen: (1) Both deposits

FIG. 21.—Stream deposit in Mazourka Canyon. Compare with Figs. 14 and 15

were formed and eroded before the deposition of the recent alluvium. (2) Both are firmly cemented, at least locally. (3) They are similar in texture, both being fine and having a low textural range. (4) Their stratification is the same, both being sorted into layers. They are dissimilar in that the constituents of the deposits at the foot of the mountains are better rounded than those in Waucobi Canyon, and the former contain no fossils. With such similarities between these deposits and the lake beds, it seems clear that the older materials northeast of Mt. Whitney station and east of Citrus are of lacustrine origin, and belong to the same formation as the lake beds in Waucobi Canyon and at Haiwee. If so, the lake in which they were deposited was shallow, and the shore lay against the

mountains immediately to the east. The dissection of the deposit probably took place subsequent to the uplift of the mountains and the draining of the lake. If lacustrine beds corresponding to them were deposited at the foot of the Sierras, they have been covered and concealed by the more recent alluvium.

The deposits in Mazourka Canyon are obviously not lacustrine, but of stream origin. They were probably laid down on the floor of a mature valley, which was tributary to the lake east of Citrus.

FIG. 22.—Photograph to show the shapes of the cobble in the terrace of Mazourka Canyon.

The differences between these deposits and those along the foot of the mountains may be taken as differences characteristic of lacustrine and fluvial deposits.

THE PRESENT FANS

DISTRIBUTION

Between Mt. Whitney station and Aberdeen there are nine separate fans at the foot of the Inyo Mountains. On the map (Plate I) they are numbered 1 to 9, beginning at the south. Of the nine fans, 1, 2, 4, and 8 are large, each covering more than a square mile, and 3, 5, 6, and 9 are smaller. All of them occur at the mouths of mountain canyons. The largest one, No. 4, is at the mouth of the largest canyon, Mazourka, though it is not so well shaped as the others. Between the mouths of the main canyons and between the main fans are some patches of alluvium too small to map and not important in any way. These patches occur at the lower ends

of very small valleys. Fans also occur along the mountains outside the mapped area. They were seen northeast of Aberdeen and at Keeler.

SHAPE AND TOPOGRAPHY

In general there are two controlling factors in the shapes of the fans. At their mountainward edges they are confined by the walls of the mouths of the canyons, from which they take their form. Their outer edges deploy slightly on the plain. Nos. 2 and 8 extend about a mile into their canyons, and No. 4 extends still farther up Mazourka Canyon. Nos. 1 and 3 show deployment on the plain. No. 2 is made up of two smaller fans, with a depression at their junction.

The surfaces of these fans are very similar to the surface of the Sierra bajada, except that all features are on a smaller scale, the fans, except No. 2, are simpler and remain separate, and these fans are not now in process of dissection. The individual fans show numerous radiating channels and low ridges similar to those on the Sierra plain, but they give the surface here a relief of no more than 7 or 8 ft. at a maximum. The ridges are almost invariably belts of bowlders. The fans are not dissected as is the Sierra bajada. The streams still flow on the surface in the radiating channels, but they flow only after the infrequent rains in the mountains.

The slope of the fans varies considerably from head to outer edge. Fan No. 8 has a slope of about 10° at its head, 5–6° midway of its length east and west, and approaches flatness at its outer edge. Fan No. 1 has a slope of more than 600 ft. per mile in its upper part. The upper part of fan No. 2 slopes westward 800 ft. in a mile. This is steeper than the average.

MATERIALS

These fans at the foot of the Inyo Mountains have not been dissected, and exposures of the material are therefore few and shallow. Some data can be collected from surface materials, there are a few shallow cuts along the channels, and one prospect pit affords a good exposure.

Each fan is made up of pieces of the kind of rock in which the canyon back of it is cut. For instance, 99 per cent of the material

of fan No. 8 is granite, the other 1 per cent scoriaceous lava and slate. All the face of the mountains here is granite, which is bordered along the edge of the Santa Anita flat by slate. Lee[1] maps a volcanic mountain southeast of Aberdeen, which doubtless explains the occasional fragments of scoriae. The fan northeast of Aberdeen is composed of bits of granite, gneiss, scoriaceous basalt, and limestone. All these rocks occur together in the walls of the canyon. Fan No. 1 is made up largely of bits of lava, sedimentary rock, and granite. No. 2 is mostly of sedimentary rock and lava,

FIG. 23.—Bowlders on the surface of fan No. 8 north of Citrus. Their size may be estimated.

with some fragments of granite. No. 3 contains a mixture of sedimentary rock, diorite, and granite, in keeping with the rocks east of it.

On the surface of the fans there are both coarse and fine materials arranged as on the Sierra bajada in diverging lines or belts from the head of the fan.

Though the bowlders are not so large as on the opposite side of the valley, they are still astonishingly large for the drainage by which they were transported. The largest bowlders seen were near the head of fan No. 8, where there are some 10–12 ft. in diameter. On fan No. 2 bowlders are especially numerous. Toward

[1] W. T. Lee, *Water Supply and Irrigation Paper, U.S. Geol. Surv., No. 181*, Pl. I.

the head of the main fan the entire surface is so covered with them that a horse cannot travel over it. The average size of the bowlders is about 1½ ft. Their number and size can be seen in Fig. 23. The photograph was taken from fan No. 8.

These bowlders show little shaping. If fragments were broken from ledges by the wedge work of ice and gravity, and then the sharp and irregular edges dulled during a short period of transportation, their present shape would result. Neither glaciation nor prolonged rolling has affected them.

FIG. 24.—Angular material in the fans at the foot of the Inyo Mountains

The fine material on the surface of the fans occurs in largest areas near the outer edges, where there are few bowlders, and the surface material has about the texture of fine gravel or coarse sand. A half-mile from the edge it is made of fragments more or less shaped by transportation, averaging perhaps 3 in. through, with some lines of larger bowlders. At the head the surface is practically covered with bowlders.

Although exposures of material beneath the surface are almost wanting, a few shallow cuts were seen. The data they afford follow:

1. In the outer edge of fan No. 8, 4 miles south of Aberdeen, is a pit dug as a placer prospect, 10 ft. deep, 15 ft. long, and 5 ft. wide. The material is all fine, there being nothing as large

as 1 in. in diameter. The pieces are distinctly angular. The section follows:

3 ft.....Fine clay and gravel, not laminated.
1 ft.....clay
2 ft.....fine gravel
½ in.....clay
3 ft.....fine gravel
2 in.....clay

2. Ten feet of material are exposed in the fan northeast of Aberdeen. It is not stratified. Angular bowlders are imbedded in a matrix of clay.

3. Near the upper end of fan No. 2, a gully affords an exposure. The section consists of both stratified and unstratified material. In the unstratified parts, the main constituent is clay, in which are imbedded numerous angular bowlders. One 3½ ft. in diameter occurs in a mass of clay.

4. Distinctly angular alluvium is shown in Fig. 24.

SUMMARY

It is apparent from the foregoing that there are two sorts of terrestrial deposits in and at the foot of the Inyo Mountains, of two distinct ages. The first deposits appear to have been made when the mountains were low and bordered by a lake. Mazourka Canyon had been cut and brought to grade, deposition taking place in its bottom from its mouth up. The deposits of the time are all fine, fairly well sorted in Mazourka Canyon, and very well sorted in Waucobi Canyon and along the mountain foot.

Conditions so changed that these first deposits were largely removed by erosion. The change was probably brought about by the uplift of the mountains, as the later alluvium is much coarser than the older. After the uplift, new canyons were cut in the mountains, and new fans deposited among the remnants of the old lacustrine deposits. This process is still going on.

SOME PROBLEMS OF THE TERRESTRIAL DEPOSITS

The fluvial deposits of Owens Valley, as described above, offer several problems. In some cases the solutions of the problems are simple and obviously correct; in others the solution is not so clear,

and there is some doubt as to the correctness of tentative conclusions; in still other cases, the solution is entirely hypothetical. In some cases various lines of explanations may have partial application to the observed features. These problems are here discussed individually.

MANNER OF FORMATION OF THE FANS AND BAJADA

CAUSES OF DEPOSITION

Material was deposited at the foot of the Sierra and Inyo mountains, primarily because of an abrupt decrease in the gradient of the streams. When the mountains were first uplifted, and precipitation fell on the slopes, streams formed and flowed swiftly down the sides, carrying material from their channels. When the base of the mountains was reached, the carrying power was suddenly and greatly decreased, and the first deposition resulted.

Once started, other factors tended to increase the process of deposition. Streams lost volume by sinking into loose material. This not only reduced the volume of the transporting agent, but also lessened the velocity of the water remaining at the surface; both these changes caused deposition.

The average relative humidity of the Sierra Nevada Mountains is not far from 60 per cent, and that of Owens Valley probably not more than 40 per cent.[1] When the streams reach the plain, evaporation is increased; hence loss of volume, loss of velocity, and decrease in carrying power. This would not be so important in the case of the Inyo Mountains, because the difference in humidity between mountains and plains is not so great there. However what little rain falls, is in the mountains rather than on the plains, and evaporation takes place more rapidly in the latter locality.

Water taken from streams by irrigation so decreases their volume in some other localities as to aid in causing deposition, but such is not the case in this region. The Sierra bajada has been undergoing dissection rather than gaining by deposition since man began to irrigate the lands, and the streams on the Inyo fans, running only after rains, are not used for irrigating purposes.

[1] For details of precipitation and evaporation in the valley, see *Water Supply and Irrigation Paper, U.S. Geol. Surv., No. 181*, pp. 17–25.

Decrease in volume and consequent decrease in velocity took place on the plains for another reason also. It rained heavily or snow melted rapidly in the mountains, and the mountain streams acquired great volume and velocity. When the rain ceased, or the temperature dropped below 32°, the flood on the plains subsided from lack of supply from above. This undoubtedly furnished conditions under which a large proportion of the material of the fans was deposited.

Glaciation has played a large part in the deposition of the Sierra bajada. Glaciers prepared immense amounts of material in the mountain canyons for transportation by streams. At the same time they furnished great volumes of water to act as the transporting agent during the melting-season. The initial volume and the load being at a maximum, deposition took place on the plains at an unusually rapid rate and to an unusually great extent.

FORMS TAKEN BY THE DEPOSITS

Deposition necessarily took place at the foot of the mountains, at the end of the mountain canyons. The streams flowed on down over the deposit it had made, until it disappeared; hence the fans slope away from the mountains. While the stream was depositing and especially at times when floods were subsiding, channels were filled, distribution took place, new channels were made and filled, and water courses changed constantly. In each new distribution the channels diverged from the mountains. The resulting feature is broader near its edge than near the head; that is, it is roughly fan shaped.

In the Inyo Mountains there is little precipitation, the canyons are far apart and small, and the fans are accordingly too far apart and have grown laterally too short a distance to have been joined. The result is a series of separate fans. In the Sierras, the streams issue at sufficiently small intervals and have built fans of sufficient size, so that they have coalesced to make a compound fan, piedmont alluvial plain, or bajada.

When fans first join, the compound fan is a series of fans, with low places between. If Oak Creek, Shepard Creek, and Hogback Creek are considered as types, there is a tendency for streams to

leave their fans and locate their main channels in the inter-fan depressions. Deposition then takes place in the depression, building it up and making a fan across the edges of two earlier fans. Presumably streams will shift back to their original positions when those positions have become lower than the site of the original depressions, through deposition in the latter. Streams then shift from fans to depressions, make fans there, shift back, build up the old fans, shift again, etc. How frequent and important this may be is not clear. If streams shift freely from higher places to depressions, it is surprising that fans of the bajada stand 200 ft. above the low places between them. The general relief of the bajada should be very slight. The water forming depositing streams probably does not adjust itself freely to the low places, though it is clear that it does so in many cases. The origin of the diverging channels is clear.

THE TRANSPORTATION OF LARGE BOWLDERS

One could hardly travel a mile on the Sierra bajada, or see the heads of the fans at the foot of the Inyo Mountains without asking how the large bowlders came to their present positions. It is essentially a problem of the means of transportation of the largest bowlders farthest from the mountains, for if they can be explained, the smaller bowlders may be considered to have been carried shorter distances by the same methods. Probably the most difficult problems are offered by the largest bowlders, such as those west of Lone Pine, 6 miles from the mountains, measuring $10 \times 20 \times 30$ ft. above ground, and the one at the Cerro Gordo power shanty, larger than the one first mentioned and $1\frac{1}{2}$ miles from the mountains, and several others in that vicinity about as large.

It is clear that these bowlders came to their present positions through the agency of water. Though their size suggests glaciers as the transporting agents, such an explanation is out of the question. The lower limit of glaciation is distinctly marked in the mountain canyons above. The glaciers did not descend to the plains. Nor is there anything in the fact of icebergs floating in a lake. The deposits with which the bowlders are associated are not lacustrine, and no lake existed in the valley during glacial

times. The surface on which the bowlders lie clearly was made by running water. The bowlders are so clearly a part of the fans, and the fans are so clearly running-water deposits, that the bowlders must be considered to have been transported by running water.

It is also clear that the bowlders were not transported according to the common and well-known methods of stream transportation. They have certainly not been rolled along the bottoms of streams in the usual way. They have not the rounded form characteristic of such motion. On the surface of the fans, furthermore, it is impossible for streams to have existed deep enough and strong enough to have so rolled these bowlders. Such streams would have to have a depth about equal to the diameter of the bowlders, be confined in a narrow channel, and flow with a velocity almost inconceivable for a stream. As the bowlders occur on the higher parts of the fans, water of sufficient depth to have carried them would have formed a sheet 20 ft. deep over the fans, and 220 ft. deep over the inter-fan depressions. Even then it would not have been confined to a narrow channel. Also the gradient of the fans is relatively low. Where the largest bowlders are, the slope is not over 6°, and west of Lone Pine not more than 3°. Bowlders much smaller than these are not now being rolled down the mountain canyons above, where the streams are sharply confined and the gradient is very high. The volume of the stream may have been sufficient to carry them *in the canyons* when the glaciers were there. The problem involves transportation *on the fans only*. They were perhaps carried to the heads of the fans by glaciers, glacial waters, and gravity. From there to their present positions, some special methods are called for.

A clue to a possible manner of transportation for these bowlders is obtained from observations of run-off water at the side of a previously dusty road after a heavy rain. Where the running water is but a small fraction of an inch deep, pieces of rock an inch in diameter are carried down stream. The moving of the large pieces involves the transportation of a very much greater amount of fine material. The movement of the large pieces is accomplished by the removal of fine material from the area immediately down stream from, and under, the lower part of the large piece. By undercut-

ting in front, and then by gravity and the push of water and sediment from behind, the large piece is pulled and pushed forward into the depression prepared for it. This process takes place over and over again, the large piece being moved down the low gradient in a halting fashion. The depth of the depression into which the piece falls is never so deep as the diameter of the fragment moved. Once started in motion, the piece is sometimes carried many times its own length by its momentum, and by the force of water and gravity. The motion is usually one of sliding rather than rolling.

It is conceivable that these same methods might operate on the surface of an alluvial fan, on a scale large enough to transport bowlders even 20 ft. in diameter distances of several miles. The bowlder starts from the head of the fan in company with a relatively large amount of fine material. The volume of the stream varies greatly from time to time, with great differences in precipitation in the mountains, and with daily and seasonal ranges in the rate of melting of glaciers. Material is deposited and rehandled time and time again. When the volume is great, fine material is removed from the front of the bowlder and from beneath its front edge, while other material is piled against its upper side, and the bowlder falls, or is pushed, or rolled over into the depression. As the flood subsides, the bowlder may be almost or completely buried, but the next flood uncovers it, and the process is completed. With sufficient time, sufficient variation in volume of water, and sufficient rehandling of material, huge bowlders may thus be transported great distances.

Would the slope of the fans be sufficient for such transportation? In the roadside rill the piece of rock moves a distance several times its own length, while dropping less than its own diameter. Suppose the bowlder 20 ft. in diameter moves 40 ft. horizontally, with a fall of 15 ft.; this would require a gradient of 1,980 ft. per mile. If it moves 60 ft., with a 10-foot drop, the gradient would be 880 ft. per mile. The average slope of the bajada is about 400 ft. per mile. This requires that the bowlder west of Lone Pine, 10×20×30 ft., move about 120 ft., or four times its own length, in dropping 10 ft., or about its own smallest diameter, if the proportions observed hold.

This is conceived to be possible. The process is greatly aided by the momentum obtained by the bowlder when it first moves toward the depression. The depression below the bowlder would not be deep, before the crowding of the material above, and the force of water and gravity would force the bowlder into it. The depression would play out very gradually down slope, giving a constant gradient down which the bowlder could roll, slide, or creep.

Obviously this process would operate to best advantage where there was the greatest volume of water, and where fluctuations of water were greatest; that is, along the main channels of the fans, and on the Sierra fans rather than at the foot of the Inyo Mountains. Bowlders are usually arranged in lines related to the channels, and they are more abundant and larger on the Sierra bajada than at the foot of the Inyos. If this method of transportation of large bowlders is not adequate, methods which are, are not known.

LENS AND POCKET STRATIFICATION

It was shown above (pp. 717–22 and 735–37) that the materials of the fans of the region are but crudely sorted, and that the different textural grades take the forms of lenses and pockets, rather than definite and continuous layers. No textural division was traceable more than 50 ft. in any cut, before it played out in one direction or another. The explanation of this seems clear.

On the surfaces of all the fans in the region are numerous radiating channels and low ridges. In Mazourka Canyon, these channels are braided in almost all directions, though along lines trending generally down valley. These surfaces represent the last deposition on the respective fans. Beneath the present surface there must be many similar surfaces, made and buried as the fan was built.

When flood waters flow over a fan, radiating channels are formed. As the flood subsides, or if the waters are overloaded otherwise, deposition takes place in the channels. The channels are filled with whatever grade of material the stream finds itself unable to carry, and the stream is forced over the side. It then makes a new channel, fills it, and overflows to repeat the process. The fan grows by the addition of long narrow strips of material, sorted

roughly into different textural divisions. These strips diverge from the axis of the fan.

No straight section can be cut in such a deposit without cutting the filled channels. If the cut is longitudinal, practically all the channels will be cut obliquely and at low angles; a few might be cut at right angles. If the fan is dissected by streams cutting down in the old channels, buried channels will still be cut obliquely, as distribution does not take place along lines exactly parallel with previous distributaries.

The filling of a buried channel, when cut along a straight line oblique to the original channel, is exposed as a lens whose length and degree of pinching out depends primarily on the obliquity of the line of cut. A channel filled, buried, and then cut at right angles reveals itself as a pocket in section, the size and shape of which depends on the size and shape of the channel. Continuous layers, uniformly thick can occur only where the depositing distributary was long, straight, and contained uniform material, and where the filling was cut along a straight line exactly parallel to itself. Obviously where exposures are along longitudinal cuts, the result is many lenses, a few pockets, and practically no continuous layers.

That this is the correct explanation of the lenses and pockets of the fans of the region is shown by a correspondence in size between lenses and present surficial channels. On the Sierra bajada, the channels are about 8–10 ft. deep on the average, and the lenses and pockets are about 8–10 ft. thick at their thickest parts. The present flood surface in Mazourka Canyon has a relief of about a foot; the lenses in the older alluvium near by have just about that thickness.

It is understood that any deposit from distributing or anastamosing streams will reveal a lens or pocket structure in straight cuts. The principle probably applies to all alluvial fans, piedmont alluvial plains, flood-plain deposits, glacial valley trains and outwash plains, and deposits on tidal deltas.

THE DISSECTION OF THE SIERRA BAJADA

A variety of events might bear causal relations to the dissection of alluvial fans. Among them are changes in climate, uplift of the

fans, down-warping of their surroundings, etc. Such events and resulting processes may be complex. The cause of dissection in this case, however, seems to be the cessation of glaciation, and the process seems simple.

All the material seen in the bajada, even to the bottoms of the canyons, shows evidence of glacial wear. Before the mountain canyons were glaciated, the fans must have been smaller and lower than now by an amount at least equal to the depths of the canyons. Glaciers were formed, which carved great amounts of material from the heads of the canyons, carried it to their lower ends, and, melting, supplied great quantities of débris-laden waters to flow out over the fan. The fans grew rapidly and became large, out of all proportion to those at the foot of the Inyo Mountains, which were not affected by glaciers.

When the glaciers in the mountains had melted away, these enlarged fans were dissected, for the same reason that a valley train is trenched. The streams now reach the fans with less material than they carried when the glaciers existed, and are able to erode material from the fan.

The matter may be looked at in another way. The pre-glacial fans, being lower than the present ones, had lower gradients and made a sharper break in gradient at the foot of the mountains, and deposition progressed. Now that the fans are higher, their gradients are steeper, and the break in gradient at the foot of the mountains is not so great, and the streams flow out over the fans with their velocities less checked than formerly. This means at least that there will be less deposition on the present fans, and, taken with the fact that the streams have less load, plays a part in the erosion of the fans.

Presumably the canyons will be deepened almost or quite to the bottom of the glacial material. This depth has nowhere been reached as yet.

DEPOSITS OF TWO AGES AT THE FOOT OF THE INYO MOUNTAINS

The older deposit at the foot of the Inyo Mountains is here considered to be a lacustrine deposit, coinciding in age with the lake beds in Waucobi Canyon and those near Haiwee. If this be

correct, the explanation of the dissection of these deposits and the later deposition of fans is not complex.

A lake existed in Owens Valley, probably in Pliocene times, and deposits were laid down in it on the flanks of the mountains. The lake was drained or dried up, and the mountains were probably uplifted. Dissection of the deposits thus exposed and uplifted followed. After erosion had removed a large part of the lacustrine deposit, deposition began at the foot of the mountains, and the present fans have been built up among the remnants of the old lacustrine deposits.

CRITERIA FOR DISTINGUISHING ALLUVIAL FAN MATERIALS

In conclusion we may bring together the distinguishing features of the materials of fans, as seen in this region. The region affords especially good facilities for the drawing of such conclusions, as it contains both running-water and standing-water deposits of similar ages.

Deposits on alluvial fans may be distinguished from those in still water, either lacustrine or marine, as follows:

1. In alluvial fans, coarse material has a wide distribution as against confinement to a narrow zone near shore in standing-water deposits.

2. Textural range in single exposures is large in fan materials.

3. Fan materials are not in general so well sorted as deposits in standing water.

4. The beds and surfaces of fans are likely to have slopes of 6–18°, as against 0–3° in standing-water deposits.

5. Fan materials are likely to have fewer and different fossils than deposits in standing water.

6. Fan material has a lens and pocket stratification, as against a sorting into more or less uniformly thick horizontal layers, as in lakes or seas.

7. Huge bowlders widely distributed vertically and horizontally in a deposit indicate that it was deposited by running water, and with a large proportion of fine material; that is, they indicate that the material is part of an alluvial fan deposit, except in cases where glaciers have affected it, or where standing waters could have

received icebergs, or where basal conglomerates are formed near shore.

8. Theoretically, fan material will be more compact *at first* than still-water deposits of the same textural grade, as each particle drops to the bottom with greater force and the film of water around each particle is not so thick. After water is drained from both deposits, still-water deposits are likely to be more cracked than fan materials, because they contract more. After cementation, still-water deposits, say of clay, will have more veinlets than fan materials of the same texture.

ON CORUNDUM-SYENITE (URALOSE) FROM MONTANA

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Specimens of a corundum-bearing rock from the property of the Bozeman Corundum Company, fourteen miles southwest of Bozeman, Gallatin County, Mont., were obtained for Stanford University by Mr. R. M. Wilke of Palo Alto, Cal. No information concerning the country rock could be obtained except the statements of Pratt in his monograph on corundum:[1] "The corundum seams vary from a few inches to three feet in thickness. . . . . Bozeman: Fourteen miles southwest of this town corundum is found in syenite." From this it would seem that the country rock as a whole is a syenite with bands or seams of the corundum rock. These bands, the writer will show, are corundum-syenite. The rarity of this type of igneous rock accounts for the present paper.

Corundum-syenites have been described only from the Urals,[2] from eastern Ontario,[3] and from the Coimbatore district, India.[4]

The corundum-syenite is a medium to coarse-grained, gray-mottled, more or less banded rock, the banding due principally to the fact that the biotite flakes are mostly in parallel position, though the other minerals are occasionally in rough, parallel position. The gneissoid corundum-syenite, as it may be characterized, is composed of microcline-perthite, biotite, and corundum with subordinate sillimanite, muscovite, zircon, and baddeleyite. The feldspar is for the most part a perthitic intergrowth of microcline and albite, though one slide shows plagioclase, orthoclase, and microcline without any perthite. On a section of the microperthite parallel to $\{001\}$ the microcline has an extinction angle of $11\frac{1}{2}°$, and the albite, one of $4\frac{1}{2}°$. In this section the albite shows only very faint albite twinning. On a section parallel to $\{010\}$ the microcline has an extinction of $-3°$ and the albite, one of $+20°$.

[1] *Bull. No. 269. U.S.G.S.*, 133, 144 (1906).

[2] Morozewicz, *Min. u. petr. Mitth.*, XVIII, 217 (1898).

[3] Miller, *Rept. Bureau of Mines*, Toronto, Canada, VIII, Part 8, 210 (1899).

[4] Holland, *Mem. Geol. Surv. of India*, XXX, Part 3, 169 (1901).

The feldspar crystals are sometimes arranged in rough *augen*. The corundum occurs in grayish-blue crystals with an average size of 5 mm. and a maximum size of about 2 cm. The corundum crystals are tabular or prismatic in habit with the common forms: *c* {0001}, *a* {11$\bar{2}$0}, *r* {10$\bar{1}$1}, *n* {22$\bar{4}$3}, and *θ* {8·8·$\bar{1}$6·3}. The most frequent combination is *acrn*.

The corundum is often surrounded by a zone of feldspar, which is nearly free from biotite. A fibrous mineral occasionally observed proves to be sillimanite as tested in fragments. Muscovite is often observed in thin, cleavable flakes. It does not appear to be an alteration of the corundum. Thin sections show a very small amount of zircon in minute prismatic crystals. The baddeleyite is a black, submetallic mineral which is usually found between the corundum and the feldspar. It occurs in rounded blebs and in prismatic crystals not over 3 mm. in size and usually only about 1 mm. in greatest dimension. The baddeleyite will be described by the author in a forthcoming number of the *American Journal of Science*.

Baddeleyite rather than zircon forms in this type of rock probably on account of the low silica percentage.

A rock sample weighing 243.6 grams was crushed, and after sizing, the constituents were separated by means of Thoulét solution. It was found that good separations could be made by panning with the Thoulét solution. The following shows the amounts of the various minerals and also the percentages by weight, assuming the loss to be equally distributed among the minerals:

	Grams	Percentage
Feldspar	136.6	62.7
Corundum	67.3	30.9
Biotite	12.6	5.8
Baddeleyite	1.1	0.5
Loss	26.0	
Total	243.6	99.9

We may assume the feldspar to be a eutectic of albite and orthoclase. Vogt gives the eutectic ratio for these two minerals as *ab*=58 per cent, *or*=42 per cent. We then have 36.4 per cent albite and 26.3 per cent orthoclase. The biotite is the only mineral

which does not have a fixed chemical composition. We may, however, assume the following percentages which are average values for biotite SiO_2=37 per cent, Al_2O_3=16 per cent, Fe_2O_3=6 per cent, FeO=15 per cent, MgO=12 per cent, K_2O=10 per cent, H_2O=4 per cent.

The recalculated chemical analysis of the rock given is as follows:

	Orthoclase	Albite	Corundum	Biotite	Baddeleyite	Total
SiO_2	17.0	25.0	....	2.1	...	44.1
Al_2O_3	4.8	7.1	30.9	0.9	...	43.7
Fe_2O_3	....	....	....	0.3	...	0.3
FeO	....	....	....	0.9	...	0.9
MgO	....	....	....	0.7	...	0.7
CaO	....	....	....	...	...	....
Na_2O	....	4.3	....	...	...	4.3
K_2O	4.4	....	....	0.6	...	5.0
H_2O	....	....	....	0.2	...	0.2
ZrO_2	....	....	....	...	0.5	0.5
	26.2	36.4	30.9	5.7	0.5	99.7

Chemically, this is a peculiar rock on account of the high alumina and low silica content. It may be called a corundum-syenite. In order to place this rock in the new quantitative classification it is necessary to convert the percentage compositions of the oxids into percentages of the standard minerals, which in this case are nearly the same as the actual minerals. In other words, the mode and the norm agree closely, biotite being practically the only critical mineral. The calculated norm of the rock is shown in table on p. 751.

All the potash goes into the orthoclase molecule, all the ferric iron and an equivalent amount of the ferrous iron go to make the magnetite molecule. The remaining ferrous oxid goes with all the magnesia to form the hypersthene molecule which requires an equivalent amount of silica. The silica remaining after deducting that required for the orthoclase, hypersthene, and zircon would naturally go into the albite molecule, but it is found that there is too much soda for this amount of silica so that the silica and soda must be distributed between the albite and nephelite according to the equations:[1]

$$x + y = \text{molecules of } Na_2O$$
$$6x + 2y = \text{available } SiO_2$$

[1] *Quant. Class. of Igneous Rocks*, 194 (1903).

in which x is the albite molecule and y the nephelite molecule. The remaining alumina goes into the corundum molecule.

	Or	Mt	Hy	Z	Ab	Ne	C
SiO_2 =44.1	19.1	...	1.7	0.2	22.1	1.0	...
Al_2O_3 =43.7	5.4	...	...	...	6.3	0.8	31.2
Fe_2O_3 = 0.3	...	0.3	...	...	...	...	...
FeO = 0.9	...	0.1	0.8	...	...	...	...
MgO = 0.7	...	...	0.7	...	...	...	...
Na_2O = 4.3	...	...	...	...	3.8	0.5	...
K_2O = 5.0	5.0	...	...	...	...	...	...
ZrO_2 = 0.5	...	...	...	0.5	...	...	...
	29.5	0.4	3.2	0.7	32.2	2.3	31.2

Orthoclase	= 29.5	F	Salic
Albite	= 32.2	F	Salic
Nephelite	= 2.3	L	Salic
Corundum	= 31.2	C	Salic
Zircon	= 0.7	Z	Salic
Magnetite	= 0.4	M	Femic
Hypersthene	= 3.2	P	Femic
Total	= 99.5		

The classification of the rock according to the new quantitative system is as follows:

$\frac{Sal}{Fem}$	$=\frac{95.9}{3.6}>\frac{7}{1}$	Class I, Persalone
$\frac{F+L}{C+Z}$	$=\frac{64.0}{31.9}>\frac{7}{1}<\frac{5}{3}$	Subclass II, Persalone
$\frac{L}{F}$	$=\frac{2.3}{62.7}<\frac{1}{7}$	Order 5, Perfelic
$\frac{K_2O'+Na_2O'}{CaO'}$	$=\frac{123}{0}>\frac{7}{1}$	Rang 1, Peralkalic
$\frac{K_2O'}{Na_2O'}$	$=\frac{54}{69}>\frac{3}{5}<\frac{5}{3}$	Subrang 3, Sodipotassic

The magmatic name of this subrang is uralose and the magmatic symbol I^2, 5, 1, 3. Only two rocks have previously been assigned[1] to uralose, a corundum-syenite and a corundum-pegmatite, both from the Urals.

[1] Washington, *Professional Paper, U.S.G.S., No. 14*, 217 (1903).

A DRAWING-BOARD WITH REVOLVING DISK FOR STEREOGRAPHIC PROJECTION

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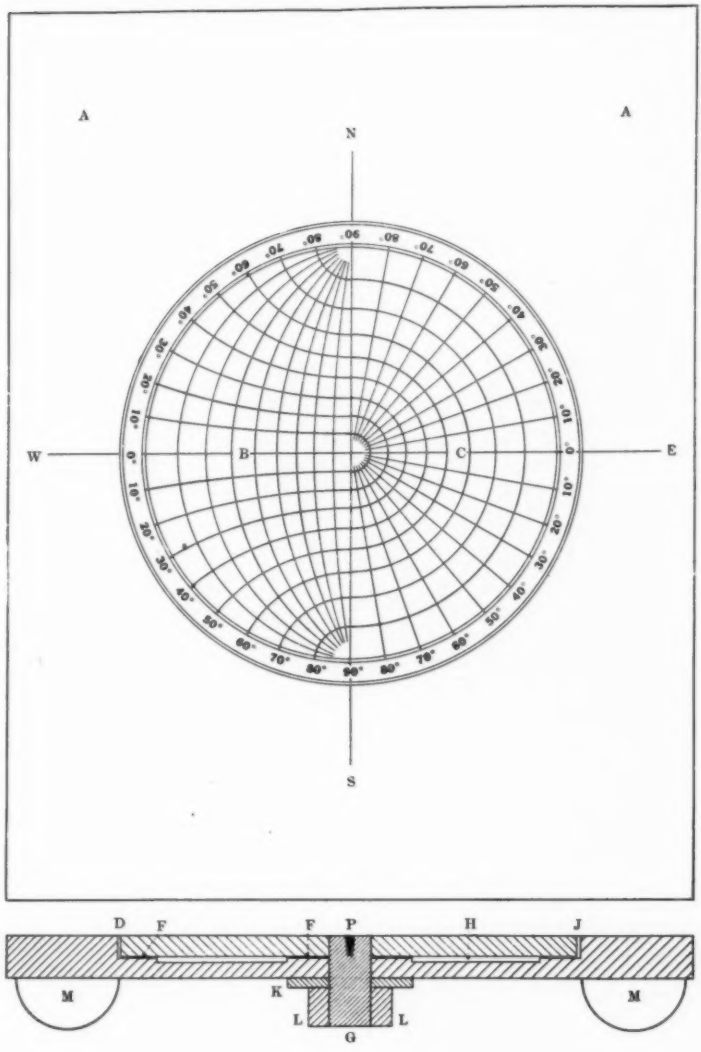
The University of Chicago

Professor Wülfing recently showed the writer a wall chart for stereographic projection which he has since described.[1] It consists of a ground glass plate back of which is pivoted a 70 cm. Wulff net which is made of pasteboard and projects beyond the glass cover so that it may be turned to any desired position. The advantages of using the Wülfing chart were so apparent that the writer has constructed a drawing-board, for the individual use of students, on a somewhat similar plan but combining with the Wulff net a half-net with the north pole at the center. The construction is simple and the board inexpensive.

In making stereographic projections by ordinary methods, one must either work out his own dimensions, use a Penfield protractor, or a net like that of Fedorow or of Wulff. Transparent nets are an improvement over Penfield's method, although one must always carefully center the net for each measurement. With the drawing-board here described, the net is revolved instead of the paper and no centering is necessary.

The board was constructed from an ordinary drawing-board, $33\frac{1}{2} \times 43\frac{1}{2}$ cm. in size. It was placed on a lathe and a recess, 22 cm. in diameter (D-J in the illustration), was turned out halfway through the board which was 2 cm. thick. A further slight cut (H) was made to reduce friction when the disk is rotated, leaving only the bearing shown at F-F. A 2 cm. hole was turned entirely through the board (P-G). To keep the dial disk (B-C) perfectly flat, it was made from a piece of three-ply, built-up pyrography board, such as is sold in all art stores. This disk, also, was accu-

[1] E. A. Wülfing, "Wandtafeln für stereographische Projektion," *Centralbl. f. Min., Geol., u. Pal.* (1911), 273–75.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rately turned on the lathe and has a diameter of 21.8 cm., which leaves, when inserted in the recess prepared for it, a very slight margin for expansion. In the exact center a 2 cm. hole was turned and into this the plug P-G was glued. P is a copper rivet set in the top of the plug to serve as a compass center. K is a metal washer and L-L a wooden knob held on the plug G only by friction. This permits its removal in case the dial should ever bind and need trimming down. M-M are knobs, one of which is glued to each corner of the board. They serve as feet to keep the button L from touching when the board is placed on a flat surface. The plug P-G fits snugly into the drawing-board and the dial will readily remain in any position to which it is turned.

The net B-C in the accompanying figure is shown divided only into parts of 10 degrees each. Actually the section B was made by gluing half a Wulff[1] net to the top of the dial disk. The mathematical center is located by a very small pit in the top of the plug P. A further guide to centering the net is a scratch circle described upon the wooden disk and having a diameter of 2 mm. more than the Wulff net. The section C of the dial is used to measure distances on horizontal small circles and vertical great circles. It was made on a sheet of cardboard by drawing circles from the stereographically projected lines of the Wulff net. These also, as well as the projected great circles which appear as radii, are drawn 2 degrees apart although they are shown 10 degrees apart in the figure. Upon the drawing-board itself the N-S and E-W lines were drawn parallel to the sides of the board.

Cutting the net in half occasionally makes it necessary to complete a vertical small circle in two lines. The curves of the right-hand net (C) might have been drawn, say in red, over a complete Wulff net, but the confusion resulting would probably cause more inconvenience than the present necessity of occasionally drawing a vertical small circle in two operations. In most cases where such circles are used, the degree divisions on the equator are a sufficient substitute for the half-net cut off. Perhaps if the lines of every fifth vertical small circle were extended over the upper half of the right-hand net, it would be a convenience.

[1] *Zeitschr. f. Kryst.*, XXXVI (1902), 14–18.

The process of drawing is extremely simple. A sheet of tracing paper is fastened to the board (A-A) by means of thumb tacks and all angles and distances are measured directly by rotating the net into the desired positions. Since in stereographic projections all circles and angles appear in true proportions, such a drawing-board should find extensive use for map drawing as well as for crystal projection.

Reviews

"Middle Cambrian Merostomata." By CHARLES D. WALCOTT. *Cambrian Geology and Paleontology*, II, No. 2.

"Middle Cambrian Holothurians and Medusae." By CHARLES D. WALCOTT. *Ibid.*, No. 3.

"Middle Cambrian Annelids." By CHARLES D. WALCOTT. *Ibid.*, No. 5.

In these three papers Dr. Walcott has described a portion of one of the most remarkable extinct faunas which any paleontologist has ever brought to light. The fossils occur in the Burgess shale of the Stephen formation, in British Columbia. Their manner of preservation is unusual, the organisms being pressed flat, the soft-bodied Holothurians Medusae, and Annelids being represented only by thin films which fortunately are darker than the shale and are usually shiny. The internal structures are often preserved in glistening, silvery surfaces, even to the fine details. The illustrations of the fossils have been beautifully executed by an ingenious process of photography by reflected light, the photographs being reproduced upon heliotype and half-tone plates.

The Merostomata contained in this remarkable fauna are referred to two new genera, Sidneyia and Amiella, both included in the order Eurypterida, and each made the type of a new family. Each genus is represented by a single species. *Sidneyia inexpectans* is a remarkable type, such as might be expected in an Ordovician rather than in a Middle Cambrian fauna, it is much the commoner of the two and some of the specimens are preserved in such a perfect condition that the structural details of the ventral appendages, even of the branchiae, can be worked out. *Amiella ornata* is represented in the collection by a single broken specimen, and is consequently much less perfectly understood.

The commonest of the Holothurians, *Eldonia ludwigi*, a new genus and species, is a peculiar, free-swimming type, with an umbrella-shaped, medusa-like body, growing to a size of 12 cm. in diameter. The spiral alimentary canal, the oral aperture and tentacles, and the water-vascular system are well shown in many of the specimens. Other Holothurians with more or less elongate, cylindrical bodies, having more the form of living members of the class, are represented by the new genera Laggania, Louisella, and Mackenzia. The Medusae are much less

common than the Holothurians; a single new genus and species, *Peytoia nathorsti*, is described, its condition of preservation being identical with that of the Holothurians.

Heretofore the existence of Annelids at the time of deposition of very ancient sediments has been inferred from the presence of certain more or less obscure burrows and trails, but here in the Burgess shale Walcott has been able to recognize eleven genera of these organisms, so perfectly preserved that not only the segmentation of the body but the most delicate appendages can be recognized. The genera are of course all new, and they belong to widely separated families, indicating a remarkable degree of differentiation at this very early period.

Descriptions of the numerous Phyllopod crustaceans which are said to be associated with the organisms discussed in the three papers here noticed, have not yet been published. They will doubtless be made the subject of another paper in this same volume of *Cambrian Geology and Paleontology*. S. W.

Seismic History of the Southern Andes (Historia sismica de los Andes Meridionales. Por el Conde Fernando de Montessus de Ballore, director del Servicio Sismólojico de Chile. Primera Parte. Santiago de Chile, 1911).

As is well known, one of the most unstable regions upon the globe is represented by the great Cordilleran backbone of South America. Yet until quite recently little has been undertaken on scientific lines within that vast region, and its seismic history has been a closed book. When, as a consequence of the object-lesson furnished by the late Valparaiso earthquake, the Republic of Chile established a modern seismological service, it very wisely decided to call to its directorship one of the foremost of living authorities upon earthquake phenomena. Already familiar with the Spanish language from years of residence in Central America, and an experienced compiler of seismic maps and catalogues, it was inevitable that the Count de Montessus would not long delay in exploiting the rich mine of seismic facts so long buried in local historical documents. This agreeable task the new director has undertaken, and the wealth of the material has proved even greater than was supposed, so that it will fill several volumes. The first of these has just appeared and is entitled "Seismic History of the Southern Andes" (*Historia sismica de los Andes Meridionales.* Por el Conde Fernando de Montessus de Ballore, director del Servicio Sismólojico de Chile. Primera Parte. Santiago de Chile, 1911).

This seismic history covers the period from 1810 to 1905. The second volume, which is now in press, will treat the much more interesting earthquake of southern Peru, Bolivia, and northern Chile. Seismologists will rather generally regret that it was necessary to print the results in the Spanish language.

W. H. H.

"The Production of Phosphate Rock in 1910." By F. B. VAN HORN. Advance chapter from *Mineral Resources of the United States* for 1910, U.S. Geol. Survey, Washington, 1911.

The total production of phosphate rock in 1910 showed an increase of a little over 10 per cent over the 1909 production. The increase came notably from Florida, with small increase from Tennessee and the western fields, and a drop in production from North Carolina. A drop of fifty-one cents per ton in the average price brought the increase in value down to a little over 1 per cent. Florida is as before by far the largest producer, giving 77.9 per cent of the total for 1910. A short chapter on methods of mining phosphate rock in the various fields is inserted.

A. D. B.

"The Manufacture of Coke in 1910." By EDWARD W. PARKER. Advance chapter from *Mineral Resources of the United States* for 1910, U.S. Geol. Survey, Washington, 1911.

The coke output of the United States in 1910 broke the record of 1907 by nearly a million tons but by no means reached the 1907 record for value. Compared with 1909 the amount increased 6.1 per cent and the value 10.9 per cent. Illinois rose from fifth to fourth rank owing to the installation of ovens at Joliet by the United States Steel Corporation, but in general the rank of producing states changed little. In 1910, 17.12 per cent of the output was from by-products ovens, against 15.94 per cent in 1909.

In spite of the increased production and higher price of coke, 1910 was not a satisfactory year from the producer's standpoint. The increased value of the coal charged into the ovens more than offset the increase in price of coke. A downward tendency in price held throughout, with the result that before the end of the year some manufacturers were running at a loss.

A. D. B.

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